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EXPERIMENTAL INVESTIGATION OF KEYED SHEAR JOINTS SUBJECTED TO A COMBINATION OF COMPRESSION AND SHEAR LOADS

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Abstract

Recently an increased attention has been given to the behaviour of keyed shear joints, which are typically used as vertical connections between precast reinforced concrete wall elements. The previous investigations have primarily focused on the load carrying capacity and the load-displacement relationship of connections exposed to pure shear. In practice, however, such connections typically carry shear loads in combination with normal tension or compression stresses. This paper describes an experimental setup, where biaxial compression can be applied in two principal directions by hydraulic actuators. The setup allows for an experimental investigation of combined loading on structural joints between precast concrete elements, with loads introduced in a controlled and adjustable manner. The experimental program consisted of 9 keyed shear connections between L-shaped precast concrete elements. The tests were performed with different levels of compressive normal stresses ranging from 0 - 4 MPa. The experimental results are presented as load-displacement curves, which show a systematic dependency on the level of normal compression. The cracking behaviour and the governing failure modes are discussed. Finally, a simple analytical equation is established to describe the load-displacement relationship of the connections.

Keywords: Precast Concrete Structures, Keyed Shear Connections, Structural Testing, Combined Loading.

1. Introduction

One of the unconditional necessities for a structure consisting of precast reinforced concrete components is the ability of the structural joints between the precast components to transfer loads in a sufficient manner. In general, two different types of joints can be identified – vertical keyed shear joints and horizontal cast joints (interfaces). Figure 1 illustrates schematically the two types of joints, including the typical loading situation of the joints when wind loads have to be transferred through the structure to the foundation. It is evident that the strength and deformation capacity of these joints are of great importance for the overall structural performance and knowledge of the behaviour during loading is a prerequisite, when the capacity of the entire structure is to be modelled.

Considering the keyed interfaces, a number of test have been made to verify the behaviour during loading, see e.g. the early work collected in SBI report 97 (Hansen et al., 1976). Later on tests were made, e.g. by Abdul-Wahab (1986), Chakrabarti, Nayak, & Paul (1988) and recently by Sørensen et al. (2016), confirming the behaviour found in the early works. Most of the investigations were conducted in pure shear and only a few experimental setups were able to introduce normal forces perpendicular to the keyed interfaces, see e.g. Fauchart & Cortini (1972). The experimental work presented in this paper focuses on the behaviour of keyed connections subjected to shear in combination with a constant compressive normal stress. The motivation for this study is primarily to clarify how the compressive stress applied normal to the interface affects the load-displacement relationship of the keyed connections and, based on the experimental observations, to establish an analytical formulation of the constitutive relationships for the joints that can be used for numerical modelling of the behaviour of precast concrete structures.

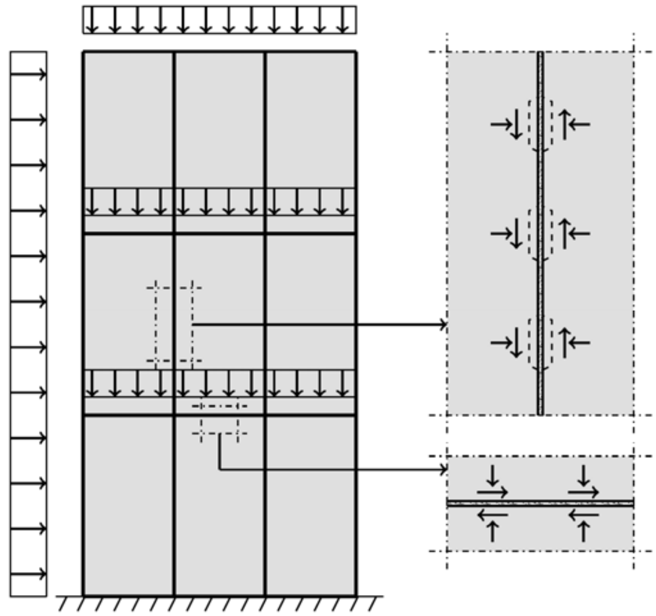


Figure 1. Example of external horizontal and vertical loads on a structure, which introduce normal and shear forces to be transferred across the connections between the precast reinforced concrete elements.

2. Experimental investigation

The experimental results presented in this paper are based on tests of 9 specimens, each consisting of two L-shaped precast reinforced concrete elements, which were joined together by three sets of U-bar loop connections cast with mortar, see Figure 2 for details of geometry and reinforcement layout.

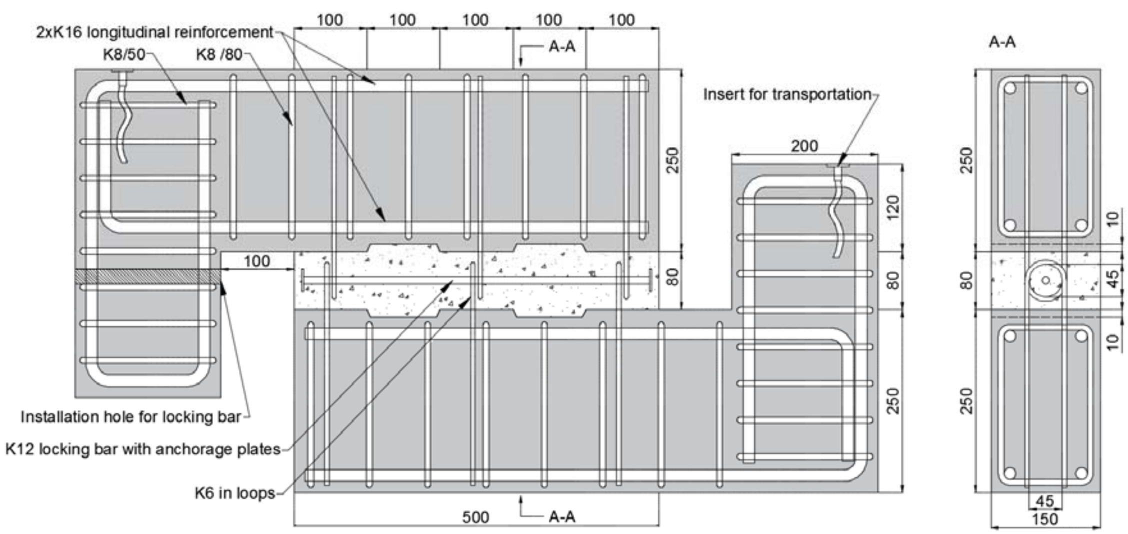


Figure 2. Geometry of test specimens containing two pair of shear keys and three sets of bend 6 mm U-bars.

The specimen design was inspired by the results obtained in the PhD study by Sørensen (2018). The number of indentations were chosen to be two, as detailed lower bound modelling showed that the development of compression struts spanning more than one pair of shear keys is highly probable, see Sørensen et al. (2018). For detection of the cracking behaviour during test, the height of the indentations was chosen to be equal to the thickness of the precast elements. The length of the connection was chosen to 500 mm, based on the length of the heavy duty roller available for the test setup. The length of the shear keys was decided based on a one-to-one ratio of shear key and spacing to the next shear key, which is a common choice in practice. The depth of the shear key was 10 mm and the diameter of the U-bar loops was chosen to 6 mm in order to achieve the more ductile governing failure mode by local shearing of the mortar in the key corners as compared to complete key cut off. When preparing the connection before casting of the mortar, the U-bar loops were carefully arranged so that they were pushed away from each other when shear displacement was imposed. In this way, the less favourable direction was tested (Sørensen et al., 2017) and results for the minimum resistance of the joint during loading could be obtained. The locking bars were provided with anchorage plates in order to limit any boundary effects.

2.1. Experimental setup

The experimental setup consisted of two hydraulic actuators placed in a custom build double frame on a strong floor in the experimental facilities of the Technical University of Denmark. The horizontal frame was designed symmetrically with two U-profiles on each side to allow for image recordings and measurements of the joint surface during test, see Figure 3. The actuators were placed perpendicular to each other with the horizontal actuator fixed in position, whereas the vertical actuator was supplied with swivels in both ends (not shown in Figure 3) to accommodate for any transverse displacements at the actuator head, when shear displacement was imposed. As supports, heavy duty rollers were used to allow for vertical and horizontal displacements of the precast elements relative to each other.

The tests were performed by applying a constant level of compressive stresses uniformly over the length of the joint (500 mm) followed by introduction of a shear load. The shear load was applied in deformation control with a constant rate of 2 mm/min (piston movement).

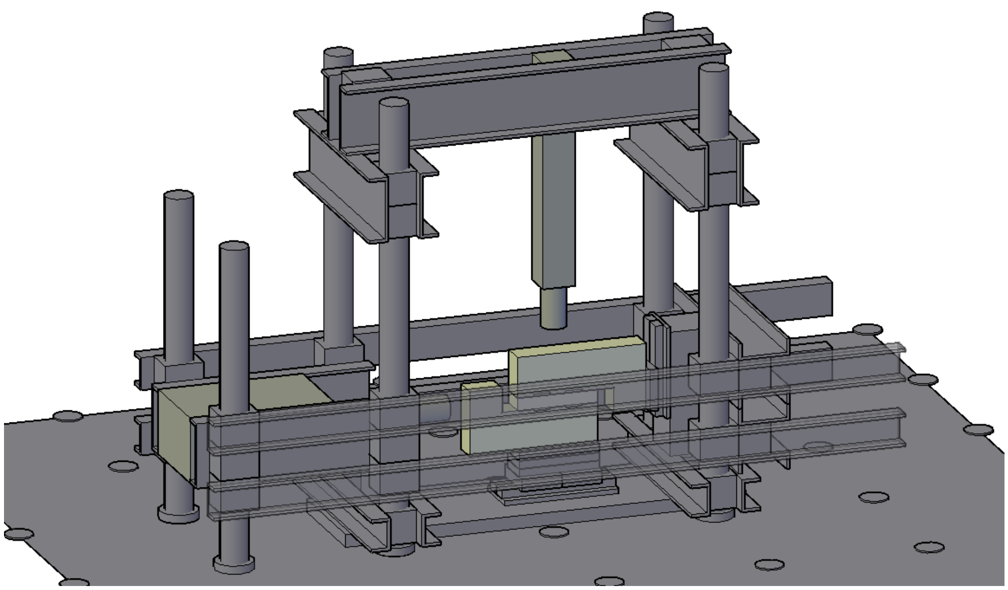


Figure 3. Test setup with two hydraulic actuators placed in a custom build frame on a strong floor.

On each specimen, the mortar surface cast against the formwork was prepared with a black and white speckle pattern for digital image correlation (DIC) analysis. On the other side of the joint mortar, conventional LVDT’s were used for recordings of the relative displacements across the connection. Transverse and longitudinal displacements were recorded in both ends of the connection.

2.2. Overview of experimental program

In Table 1 an overview of the test specimens can be seen, including the amount of nominal compressive stress applied to the connection and the maximum shear load achieved during the test. Two specimens were named U for uncompressed conditions and six specimens were denoted with a C for compressed conditions with respect to the keyed interfaces. One test was performed where the compressive normal stress was changed during the test.

Table 1. Material properties of precast elements and joint material, compressive nominal normal stress applied during test, and maximum shear load recorded during test.

Specimen ID	Element properties				Joint properties					Normal load		Results
	Concrete	U-bars			Mortar		Locking bar					
	f_c [MPa]	ϕ [mm]	f_y [MPa]	f_u [MPa]	Age [days]	f_c [MPa]	ϕ_L [mm]	f_{yL} [MPa]	f_{uL} [MPa]	N [kN]	σ_n [MPa]	P_{max} [kN]
U1	56.6	6	522.4	612.6	46	34.5	12	579.5	686.8	0	0	192.6
U1					46	34.5				0	0	195.3
C1					47	34.5				50	0.67	266.0
C2					47	33.6				100	1.33	281.5
C3					47	33.6				150	2.00	323.9
C4					47	33.6				200	2.67	359.0
C5					42	36.5				250	3.33	407.5
C6					47	33.6				300	4.00	424.1
Com1					49	36.8				100/150/ 250/300	1.33- 4.00	318.7 (at 2 MPa)

3. Test results

3.1. Experimental observations

The use of digital correlation allowed for identification of the cracking behaviour of the mortar during the test. The test results appeared very consistent with the same overall behaviour during the entire test range (all specimens suffered key corner shearing). In Figure 4 examples of the cracking behaviour of Specimen C3, which were tested with a compressive normal stress of 2.00 MPa, can be seen.

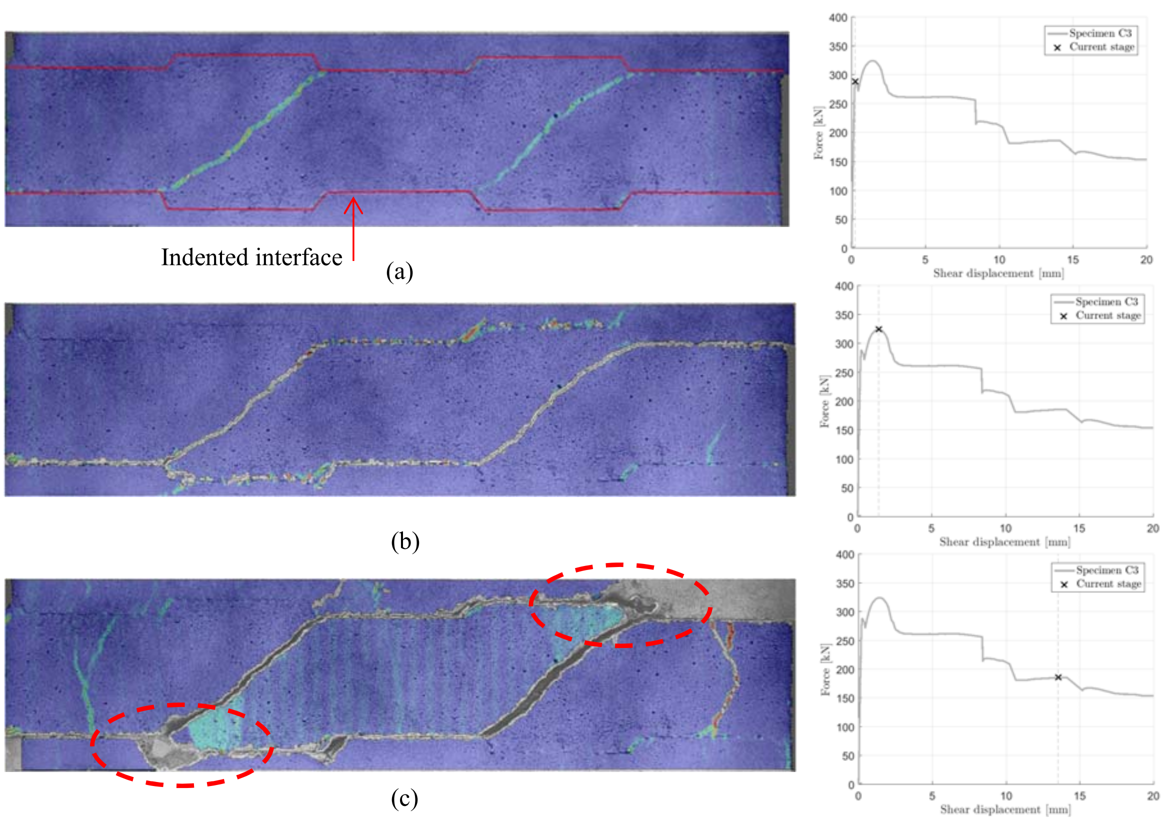


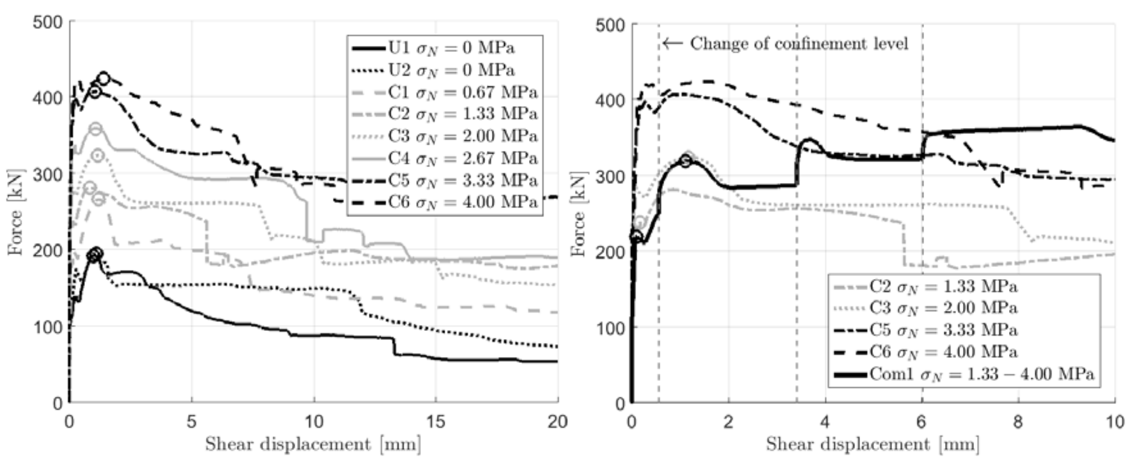
Figure 4. DIC recorded major strain field during selected stages of the test, Specimen C3.

The behaviour of the connection during test corresponded well with earlier experimental results, see e.g. Hansen et al. (1976). After a very stiff initial response, diagonal cracks between the corners of the shear key pairs emerged, even before reaching the peak capacity of the connection (Figure 4 (a)). The peak load (Figure 4 (b)) and the subsequent drop in load was associated with failure of the mortar in the key corners. In the remaining duration of the test, the displacements accumulated in the existing cracks seen at the peak load (Figure 4 (c)). In the later stage of the test, it was clear from the DIC recordings that failure had occurred in the key corners. This was confirmed by post-test examination of the grout, see Figure 5. The U-bar deformation also corresponded well with the displacement pattern recorded by DIC.

Figure 5. Example of post-test observations of extensive U-bar deformation (red circles), rupture of locking bar (red dotted circle), and local mortar failure in the key corners (red dashed circles), Specimen C3.

3.2. Load-displacement relationships

Figure 6 contains the tested load-displacement relationships for all the specimens. The displacements are taken only as relative displacements in the longitudinal direction measured by the LVDT's. In general, it can be seen that the response curve is shifted upwards as the level of compressive stress increases. In the curves, some sudden drops appears due to rupture of a U-bar leg (approx. 20 kN drop) or rupture of the locking bar (approx. 50 kN drop). The transverse displacement (not presented here) decreases in magnitude as the compressive stress increases. This is valid in the entire displacement range of the test.



(a) (b)

Figure 6. Tested load-displacement relationships with indications of the maximum recorded load.

In Figure 6 (b), the results of test Com1, where a combined loading sequence was applied, can be seen. The changes in applied compressive stress are indicated with a dashed vertical line. The results of Specimen Com1 are compared to the results of tests where the level of compressive stress was kept constant throughout the test. It can be seen that when the compressive stress is increased, the connection is able to find a new state of equilibrium with a load-displacement behaviour that is similar to the results of a test where the compressive stress is kept constant at a similar level from the beginning. This indicates that the shear behaviour of the connection at any given shear displacement is proportional to the level of compressive stress and independent on the load history (as far as an increase in normal pressure is concerned).

4. Analytical equations for the load-displacement relationship

To model the behaviour of an entire precast concrete structure (e.g. the one shown in Figure 1) it is necessary to have a fair estimate of the behaviour of the joints in a well-defined displacement regime. However, the aim of the present paper is not to develop a mechanical model for the load-displacement response of the joints. The purpose is rather to establish - in an empirical manner - a simple analytical equation that fits the tested load-displacement relationships with only a few input parameters. As a single mathematical equation is sought, it is not possible to estimate the exact stiffness of the pre-peak regime nor is it possible to capture the changes stemming from e.g. mortar crushing or reinforcement rupture. It should rather be seen as an attempt to estimate the amount of energy required to displace two precast elements relative to each other in a given displacement regime.

4.1. Load-displacement relationship for loading in pure shear

First, the uncompressed situation is considered. A simplified version of the expression for the stress-strain relationship for concrete in compression, used by e.g. Wang, Shah, & Naaman (1978) and Attard & Setunge (1996), is considered:

$$\boldsymbol{Y} = \frac{\boldsymbol{AX+BX^2}}{\boldsymbol{1+CX+DX^2}} \tag{1}$$

Initial curve fitting revealed that the following simplified form of Equation (1) was sufficient for the behavior of a keyed shear connection loaded in pure shear:

$$\boldsymbol{P_0(\delta)} = \frac{\boldsymbol{a\delta}}{\boldsymbol{1+b\delta+\delta^2}} \tag{2}$$

Here, P_0 is the shear load and δ is the relative shear displacement between the two precast elements. The benefit of the chosen relationship lies primarily in the number of data point required to derive the unknown parameters. In the following, the peak load, P_{max}, at the displacement δ_P, and a residual capacity, given as a fraction of P_{max}, at a chosen maximum displacement, δ_{max}, is considered:

$$\boldsymbol{P_0(\delta_P) = P_{max}} \tag{3}$$

$$\boldsymbol{P_0(\delta_{max}) = \beta P_{max}}, \qquad 0 \leq \beta \leq 1 \tag{4}$$

The two unknown parameters from Equation (2) can be found from:

$$\boldsymbol{a = \beta P_{max} \frac{(1-\delta_P\delta_{max})(\delta_P-\delta_{max})}{\delta_P\delta_{max}(1-\beta)}} \tag{5}$$

$$\boldsymbol{b = -\frac{\delta_P^2\delta_{max}-(1+\delta_{max}^2)\beta\delta_P+\delta_{max}}{\delta_P\delta_{max}(1-\beta)}} \tag{6}$$

4.2. Load-displacement relationship for a keyed connection exposed to compression normal load and shear displacement

Considering the test results reported in Figure 6, it can be seen that the increase in capacity is more or less proportional to the compressive normal stress applied and that it appears to be valid in the entire tested displacement regime. For that reason, the capacity of a compressed keyed connection can be estimated by adding a contribution to the basic curve derived for the uncompressed case:

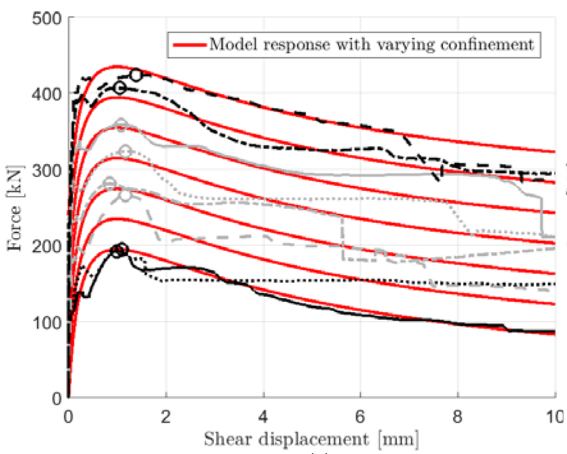
$$\boldsymbol{P(\delta, N) = P_0(\delta) + \mu N(\delta)} \tag{7}$$

It should be noted that Equation (7) can be used also for cases where the compressive normal stress is changed.

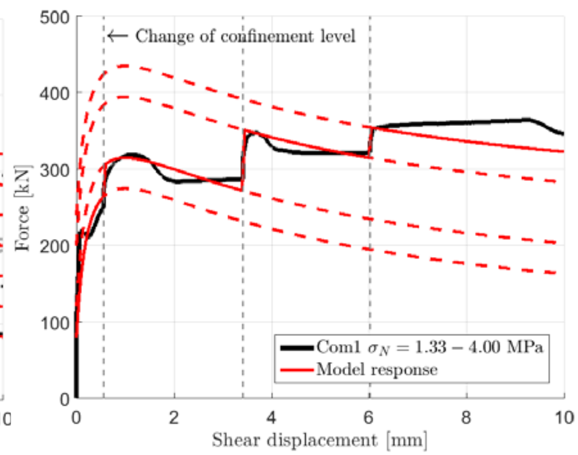
4.3. Comparison of models to test results

From the reported test results, it is found that the peak load appears after approx. 1 mm of shear displacement. This is confirmed by the investigation of Fauchart & Cortini (1972) and for this reason δ_P is taken as 1 mm in the following. The peak load can be estimated by use of a number of models, where the use of limit analysis, either upper bound solutions, e.g. (Sørensen et al., 2017), or lower bound solutions, e.g. (Sørensen et al., 2018), would be a reasonable choice of model. In the following, the peak load is simple chosen as 195 kN as it corresponds well with the present test results. Furthermore, it is estimated that the residual load level at a shear displacement of δ_{max} = 20 mm is approx. 25% of the peak load, i.e. β = 0.25. The choice of the latter data point should be chosen carefully, as it may influence the pre-peak behaviour of the curve.

The comparison between the test results and the proposed equation can be seen in Figure 7, where a value of μ = 0.8 is used. In Figure 7(b) it can be seen how the results of Specimen Com1, where different levels of nominal compressive stress was applied during the tests, comply with the proposed equation. The overall agreement is satisfactory, even when the connection is exposed to very large shear displacements. As mentioned, it is not possible to capture the sudden cracking of the mortar or a possible rupture of the reinforcement, however, the overall behaviour of the connection exposed to shear displacements is well-estimated.



(a)



(b)

Figure 7 Comparison of tested response with proposed equation, (a) for tests with a constant amount of compressive normal stress and (b) where the level of compressive normal stress was changed during test.

5. Conclusions

An experimental setup for biaxial testing of structural joints has been presented. The custom build frame contained hydraulic actuators for application of compressive loads in two directions perpendicular to each other and the support conditions consisted of rollers, which allowed for unrestricted relative displacements between the two precast elements. Results were presented from tests on keyed shear connections, where compressive normal stress was applied to the entire length of the connection followed by introduction of shear displacement between to the precast elements.

The results showed a clear dependency between the load-displacement relationship and the applied compressive normal stress in the entire displacement regime tested. The use of digital image correlation allowed for identification of the cracking behaviour during the test and also for identification of the governing failure mode, which corresponded to the peak load of the connection. All specimens failed by local key corner shearing as a result of the small key depth of 10 mm.

An analytical equation for prediction of the load-displacement relationship was presented based on the test results. It appears that the load-displacement relationship for a connection, where compressive stress is applied, can be estimated by adding a simple friction contribution to the response of an uncompressed connection.

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