- Technical Paper -

FINITE ELEMENT ANALYSIS OF KEYED MORTAR JOINTS FOR PRECAST CONCRETE PANELS

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ABSTRACT

As connections and joints between precast concrete parts represent locations of singular links, the behavior of the precast concrete structures at both serviceability and ultimate strength conditions is dependent on the behavior of such joints. Assessing analytically the characteristics and behavior of such joints under combined loads is an important issue. This paper reports some results of an analytical study carried out based on a commercial FE code to simulate the behavior of keyed mortar joints of different configurations under uniform shear and normal stresses until failure.

Keywords: concrete shear key, mortar joint, adhesion, friction, finite element, calibration analysis

1. INTRODUCTION

Precast concrete structures have become more and more popular in construction resulting from the demand for economical and safe design, as connection methods and hardware (devices) for precast structural elements had known important developments. Precast shear walls/panels, being of full precast systems or partial precast systems, have extensively been adopted for new buildings or for existing buildings when rehabilitated, to resist lateral loads of different origins, including earthquakes. As connections and joints introduce discontinuities and represent locations of singular links, the behavior of the precast concrete structures or the rehabilitated existing structures at both serviceability and ultimate strength conditions is dependent on the behavior of the joints between the assembled/connected parts. Thus, they are extremely important and should maintain the overall integrity of the construction, especially in high-seismic prone areas. Compression and shear forces across assembled/connected structural elements are transmitted through such joints being keyed or not. Whereas the shear strength of flat joints is governed by friction mechanism along the contact interface, the shear strength of keyed joints is governed by two mechanisms, the first one concerns the friction along the head surface of the key and the second one concerns the bearing/wedge effect of the shoulder surface of the key. The common practice is to use castellated or grooved keys, distributed over the joint length with a regular pitch, to provide an improved interlocking performance in comparison to flat joints. These grooved or castellated keys are mostly unreinforced due to their small size. As fitting imperfections that exists in keyed dry joints reduces their overall shear capacity, grout with an adequate thickness is used to mitigate the effects of such imperfections between assembled/connected elements. Whereas epoxy is the most common filling material used for joints of bridges [1, 2] as very thin layers are required to link elements, cement mortar is commonly used for buildings [3, 4, 5]. Assessing analytically the characteristics and behavior of such joints under combined loads is an important issue that helps evaluate appropriately the global behavior of buildings containing such joints. Based on experimental results, the most significant parameters that affect the shear behavior of the keyed joints are the confinement stress, thickness of grout, shape of the key, surface preparation, concrete strength, contact area of the joint and friction-coefficient between concrete-to-concrete surfaces [1]. Whereas various analytical studies [6, 7, 8, 9] have been carried out, the broad range of the investigated issues and differences in the used analytical tools and methods induced discrepancies in results and have not helped reach some consent and appropriate conclusions. Qualitatively, shear mechanisms across joints are well known, but there is no consent regarding their quantification. Furthermore, since castellated keys are cumbersome while setting formworks, especially when the keys are small and numerous, undulated (sinusoidal) profiles may provide an economic advantage, as well as reduce overall construction time, as they are expected to bring ease of fabrication when setting formworks, resulting in continuous undulated-shape keys over the joint length [10, 11]. Unfortunately, few investigations have been carried out on sinusoidal undulated joints, due probably to the limited contact surface between keys' shoulder faces of joints and the associated contact stress concentration when the interface crack width increases.

In this paper, the analytical study carried out by the authors based on Ls-Dyna FE code [12] to simulate the behavior of keyed mortar joints of different configurations under uniform shear and normal stresses

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until failure, while considering adhesion, friction and nonlinear behaviors of materials and interfaces, is summarized. The analytical results of two configurations of keys were calibrated by the results of the experimental work carried out by Machida et al. [13], namely the crack pattern, load-displacement/slip relationship and maximum strength. These test results were used to evaluate the main parameters (adhesion and friction coefficient) on the interface planes of the keyed mortar joint. Then, the results of this study are intended for assessing analytically the shear strength and deformation of precast infill shear walls where panel connections are with or without shear keys.

2. MODEL CALIBRATION

2.1 Test Specimens and FE Model

The 3D FE basic model used in this study was similar for all the key configurations and based on the test performed by Machida et al. [13] in which each specimen was composed of a lower and an upper concrete members and a high-strength grout mortar layer in between. The grout mortar layer was embedded for a certain depth into the lower concrete member of 2 specimens (C2-C, W2-C). An outline of the tested specimens, material and configuration of joints is shown in Fig.1 and Table 1. It is worth to mention here that the small-width part of the upper concrete member represents a portion of a concrete panel and the plywood formwork used at the keys was of relatively smooth face. Under combined axial and lateral loading, all tested specimens experienced, at first, cracks along their interfaces. Then, for the specimens C2-C and W2-C with an embedded grout layer, they experienced, shear cracks developed on the wall part and extensively expanded when the grout layer failed by shear, resulting in a lateral strength decrease more abrupt for the specimen C2-C than for the specimen W2-C, which might be explained by the abrupt form of the keys' shape that resulted in a concentration of compression stresses at the obtuse angle of the shear keys, in contrary to the specimen W2-C, which has a smooth varying shape. As for the specimen W1-C without an embedded grout layer, it experienced slipping, shear cracks in the grout layer followed by shear cracks in the wall part, resulting in a smooth decrease of the lateral strength.

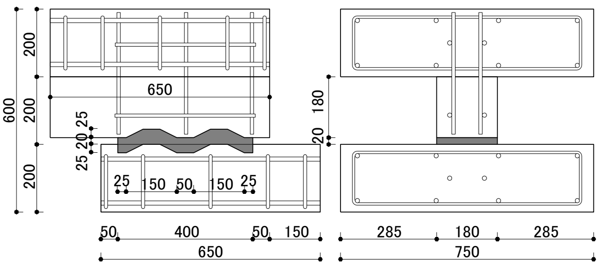
An outline of the models is depicted in Fig.2. A total of 3 specimens were modeled and analyzed: one castellated keyed joint (C2-C), one waved (sinusoidal) keyed joint (W2-C) and one combined flat-sinusoidal keyed joint (W1-C). The interface of models W1-C and W2-C, shaped by straight lines, was slightly altered vertically from the actual sinusoidal curve reaching a maximum deviation of 3.1% (0.28mm) in the area close to the sine peak. A similar and constant compression load was considered for all type of joints (Axial load ratio 0.024 counted based on the concrete strength of the upper part of the specimens).

Commercial software Ls-Dyna (R10.1) was used

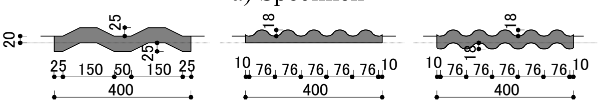
Table 1 Material characteristics (test data)

Type	Young's Modulus (kN/mm²)	Compressive strength (N/mm²)	Tensile strength (N/mm²)
Upper Concrete	31.06	43.1	2.81
Lower concrete	36.15	84.9	3.80
Grout mortar	19.66	70.4	2.06

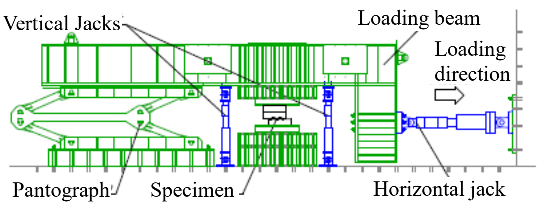
Steel type	Young's Modulus (kN/mm²)	Yield strength (N/mm²)	Tensile strength (N/mm²)
D13 (SD345) for stub	188	381.3	558.4
D13 (SD295) for panel	187	353.3	505.5



a) Specimen

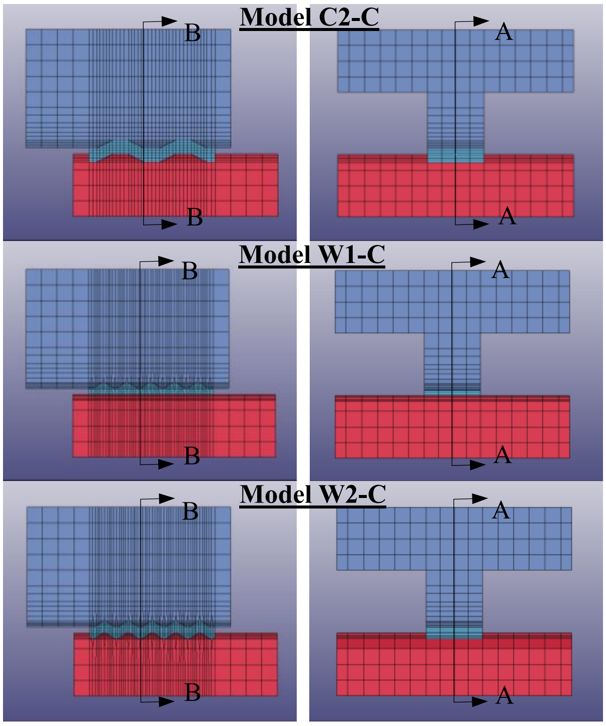


b) Mortar joint configuration



c) Loading setup

Fig.1 Outline of tested specimens and loading



Section A-A Section B-B

Fig.2 Outline of analytical models

to perform all FE analyses. Concrete and mortar were modeled as solid elements (8-node brick elements) where a relatively high density mesh was used at the location of the grout mortar layer and the concrete parts adjacent to it. Steel bars were explicitly modeled as beam elements incorporated into the concrete mesh between nodes.

Similar load conditions as in the test were reproduced in the models. Material data from the test were used in the validation. The model concerned the tested specimens and did neither include the whole loading setup nor the fixing bolts/bars and their forces. To accurately represent specimens' fixation conditions of the test, boundary conditions were applied to the wide part of the lower concrete member of the specimens by restraining all its movements (vertical and horizontal displacement and rotations). The vertical compression load was applied at the top surface of the rigid part set on the upper concrete member of the specimen. Horizontally, displacement-controlled monotonic loading was applied over the rigid part and wide part of the upper concrete member, while their other movements were restrained except the vertical displacement.

2.2 Material Modeling

The continuous surface cap (CSC) model was used for the constitutive material behavior for concrete and grout mortar. This cap model is characterized by a smooth and continuous intersection between the shear yield surface and hardening cap. For setting up the model input, in this study, default material parameters were requested based on the unconfined compressive strength as an input.

Plastic kinematic model was used for the constitutive material behavior for steel. This elastic-plastic model is suited to model hardening plasticity. The needed input was Young's modulus, the yield strength, tangent modulus and effective plastic strain.

2.3 Interface Modeling

To treat the interaction at the interface between concrete and grout mortar and tie their solid elements, tie-break surface contact elements were used, where surfaces which are initially in contact are tied and their tangential motion is inhibited until failure occurs (interface tension is lost), as shown in Fig.3 for the behavior of contact elements. The failure criterion has normal and shear components (Eq.1). The needed input was the friction coefficient, normal failure stress and shear failure stress.

$$(\sigma / \sigma_t)^2 + (\tau / \tau_0)^2 = 1 \qquad (1)$$

where,

τ : shear stress at interface

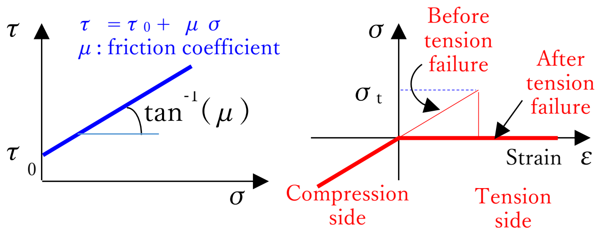
τ_0 : adhesion shear strength at interface

σ : normal stress at interface

σ_t : tensile stress at interface

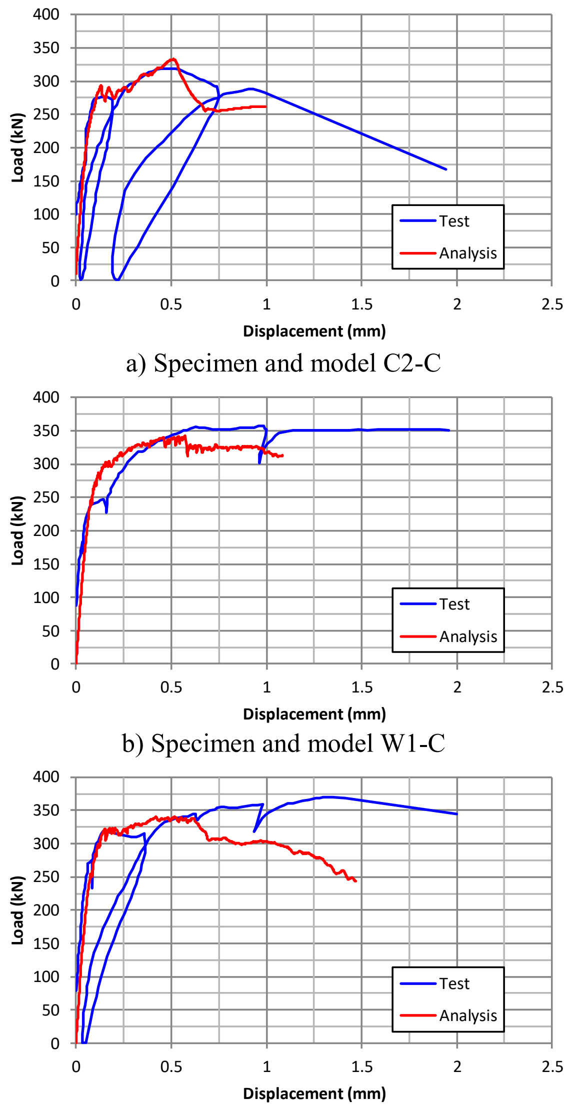
2.4 Calibration Results

Normal (tensile) and tangential shear components as well as friction coefficient at the interface between concrete and grout mortar were obtained by calibrating the model so that the load-displacement/slip curves, crack patterns and failure modes from the FE analysis matched the experimental results for each joint configuration and vertical loading. The final analytical results in terms of the force and displacement/slip at the joint obtained after multiple trials and seemed acceptable are shown in Fig.4. A summary of the final parameters of the calibrated interface models between concrete and grout mortar is presented in Table 2. The analytical and



a) Shear stress component b) Normal stress component

Fig.3 Behavior of interface contact element



a) Specimen and model C2-C

b) Specimen and model W1-C

c) Specimen and model W2-C

Fig.4 Comparison of analytical and test horizontal load-displacement curves test values of the ultimate strength are also listed in the same table.

(1) Load-deformation relationship and ultimate strength

A comparison of horizontal load-displacement curves obtained from the calibrated models and experiment is illustrated in Fig.4. Generally, the analysis could reproduce the global behavior of the three specimens and their joint patterns. The analytical results approached fairly the experimental data in terms of stiffness, deformation and ultimate strength. Therefore, some discrepancies can be noticed at some parts of the curves, due probably to: ① some differences in the material characteristics, especially the parts close to the interface areas, ② non-uniformity in the actual interface characteristics along every interface (contrary to the analysis in which uniformity of characteristics along every single interface was considered), ③ some differences between the actual key-shape and that of the model in the case of sinusoidal keyed joint (models W1-C and W2-C), and ④ some uncontrolled movements of the upper concrete part during loading (contrary to the analysis in which the upper concrete part of the model was restrained against rotations). Therefore, whereas the analytical ultimate strength of models C2-C and W1-C occurred almost at the same deformation level as in the test, that of model W2-C occurred a little bit earlier than in the test. As to the analytical values, they were very close to the test values (Table 2) where the ratios of the test value to the analytical value of the models C2-C, W1-C and W2-C were 0.96, 1.04 and 1.09, respectively.

(2) Crack pattern and failure mode

A comparison of some photos of recorded cracks during testing and the distribution of the analytical maximum principal strains of the models at the time of the maximum strength is illustrated in Fig.5. For each model, the distribution of the analytical maximum principal strains was reasonably compatible with the crack pattern observed on the corresponding tested specimen, suggesting similar failure modes including splitting of the concrete part from the grout part or slipping along the interfaces. Therefore, whereas in the test crushing of concrete or grout was observed beyond the maximum strength at some locations along the upper interface of the specimens C2-C and W1-C, in the analysis, the minimum principal stresses/strains suggested no crushing for all models.

(3) Model interface parameters

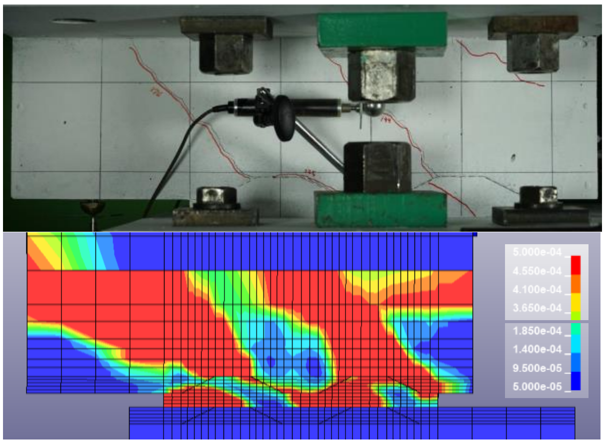
The final parameters of the calibrated interface models between concrete and grout mortar presented in Table 2 indicated a discrepancy in the analytical results that might have been affected by various factors including the configuration of key-shapes. It is worth to mention here that in each model when similar parameters were used for the upper and lower interfaces the analytical results in terms of load-deformation relationship, crack pattern and maximum strength were extremely not satisfactory and far from the test ones.

Although the face of the used formwork were relatively smooth, the obtained friction coefficients (μ) for the interfaces of the three models were generally higher than the defined value (0.6) for not-roughened

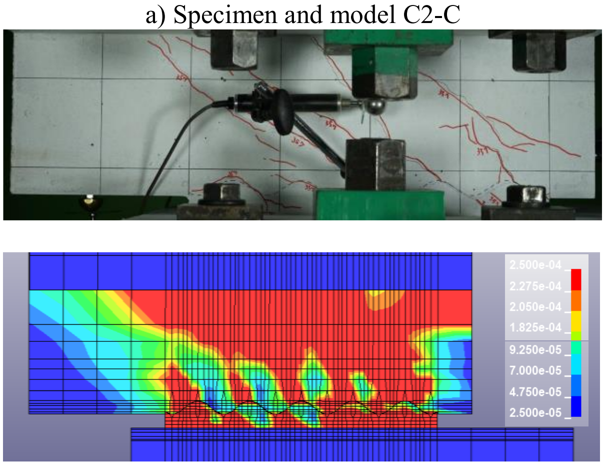
Table 2 Analytical parameters and results

Model		μ	τ_0 (N/mm^2)	σ_t (N/mm^2)	$Q_{anal.}$ (kN)	Q_{test} (kN)
C2-C	UI	1.4	4.3	2.5	333	319
	LI	1.4	4.3	2.5		
W1-C	UI	0.85	4.5	1.6	342	357
	LI	1.75	10.8	3.8		
W2-C	UI	1.2	3.5	1.9	340	370
	LI	1.5	5.6	3.0		

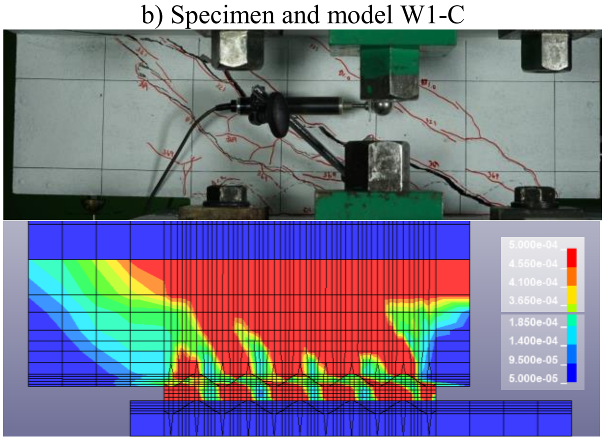
UI: upper concrete-grout interface, LI: lower concrete-grout interface, μ: interface friction coefficient, τ_0: interface adhesion shear strength, σ_t: interface normal (tensile) strength, Q: maximum strength



a) Specimen and model C2-C



b) Specimen and model W1-C



c) Specimen and model W2-C

Fig.5 Comparison of crack pattern and analytical maximum principal strain distribution at maximum strength concrete-concrete connections that is given in some design guidelines for precast concrete connections [14, 15, 16], but they seemed acceptable when referring to the test database gathered by Krc et al. [17] where even higher values are cited. Therefore, the obtained values of the apparent friction were different from a model to another and even from an interface to another of the same model, where the values obtained for the upper interfaces were lower than those of the lower interface, which might be explained by the difference in the concrete of the upper and lower parts of each specimen. The obtained friction values of the upper interface ranged from 0.85 to 1.4 and those of the upper interface ranged from 1.4 to 1.75.

As to the adhesion shear strength (τ_0) of the interfaces for the three models, the obtained values ranged between $0.06F_c$ and $0.15F_c$ (Table 3) where F_c is the smallest compressive strength value of the adjacent concrete and grout along an interface, and the highest value was obtained for the flat interface (lower interface) of Model W1-C. The mentioned range is lower than the value $0.2F_c$ based on shear tests and suggested by Miyauchi et al. [18], and higher, as shown in Table 3, than the value $0.5\sqrt{F_c}$ defined in AIJ guidelines [14] for shear key joints of precast elements.

As to the normal (tensile) strength (σ_t) of the interfaces for the three models, the obtained values ranged between $0.24\sqrt{F_c}$ and $0.45\sqrt{F_c}$, as shown by the ratios ($\sigma_t/\sqrt{F_c}$) in Table 3, where F_c is the smallest compressive strength value of the adjacent concrete and grout along an interface, and the highest value was obtained for the flat interface (lower interface) of Model W1-C. The obtained values seemed revolving around $0.33\sqrt{F_c}$ that is defined in AIJ design guidelines [19] for the tensile strength of concrete material, but were generally not compatible with the Brazilian test results listed in Table 1.

Table 3 Analytical shear and tensile strength ratios

Model		τ_0 / F_c	$\tau_0 / \sqrt{F_c}$	$\sigma_t / \sqrt{F_c}$
C2-C	UI	0.10	0.66	0.38
	LI	0.06	0.51	0.30
W1-C	UI	0.10	0.69	0.24
	LI	0.15	1.29	0.45
W2-C	UI	0.08	0.53	0.29
	LI	0.08	0.67	0.36

UI: upper concrete-grout interface, LI: lower concrete-grout interface, τ_0: interface adhesion shear strength, σ_t: interface normal (tensile) strength, F_c: smallest strength value of adjacent materials (concrete and grout) of Table 1

3. CONCLUSIONS

An analytical study was carried out based on Ls-Dyna FE code to investigate the behavior of keyed mortar joints of different configurations under uniform shear and normal stresses until failure, while considering adhesion, friction and nonlinear behaviors of materials and interfaces. The analytical results were calibrated by the results of an experimental work done by one of the authors. The calibration considered the crack pattern, load-displacement/slip relationship and maximum strength to evaluate the main parameters (adhesion and friction coefficient) on the interface planes of the keyed mortar joint. The results of the study showed that:

(1) Generally, the analysis could reproduce the global behavior of the specimens and their joint patterns, and the results approached fairly the experimental data in terms of stiffness, deformation, crack pattern and ultimate strength.
(2) The obtained interface parameters of the calibrated models indicated a discrepancy in the friction coefficient, adhesion shear strength and normal strength results that might have been affected by various factors including the configuration of key-shapes.
(3) The obtained friction coefficients for the interfaces of the studied models were generally higher than the value (0.6) defined for not-roughened concrete-concrete connections by some design guidelines for precast concrete connections, but they seemed acceptable when referring to various tests.
(4) The adhesion shear strength of the interfaces for the studied models ranged between $0.06F_c$ and $0.15F_c$, where F_c is the smallest compressive strength value of the adjacent concrete and grout along an interface.
(5) The normal strength of the interfaces for the studied models seemed revolving around $0.33\sqrt{F_c}$ that is defined in AIJ design guidelines for the tensile strength of concrete material.

These results are intended as a basis for another coming study concerning the analytical assessment of the shear strength and deformation of precast infill shear walls where panel connections are with or without shear keys.

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