13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 631

DESIGN METHOD AND COMPOUND EFFECT CONSIDERING DEFORMATION OF SHEAR TRANSFER ELEMENTS IN PRECAST CONCRETE CONNECTIONS

Katsuhiko NAKANO[1] and Yasuhiro MATSUZAKI[2]

SUMMARY

Shear transfer across a definite interface must frequently be considered in the design of precast concrete connections. As the following various resistances in the effecting shear transfer strength are given: (1) Dowel action of joint bars, (2) Direct shear resistance of concrete shear-keys, (3) Friction with the axial compressive force, (4) Adherence of the concrete surface. The purpose of this paper is to reveal the compound effects of the various resistance elements.

Basic experiments on the interface shear transfer at the precast joint faces were carried out. Ten panel type specimens with the same dimensions were tested. As the conclusion, the relation of the shear transfer mechanism and shear displacement behavior in the concrete connection is clarified. Also the evaluation equation of the shear transfer strength with consideration to the shear displacement conformity is proposed.

INTRODUCTION

The general design method for the precast concrete buildings has not been established, especially for the details of connections. The behavior of precast concrete structures subjected to earthquakes may be greatly influenced by the resistances of various elements within precast concrete connections.

The factors influencing shear transfer strength are considered as follows: (1) Characteristics of the shear interface, (2) Characteristics of the reinforcement, (3) Mechanical properties of the concrete, (4) Direct stress acting parallel and transverse to the shear interface. The shear resistance elements in the concrete connections are assumed as follows: (1) Dowel action of joint bars, (2) Direct shear resistance of concrete shear-keys, (3) Friction with axial compressive force, (4) Adherence on the concrete surface. The concrete

[1] Assoc. Prof., Niigata Institute of Technology, Niigata, Japan. Email: nakano@abe.niit.ac.jp
[2] Prof., Tokyo University of Science, Tokyo, Japan, Email: ymatsuzaki@rs.kagu.tus.ac.jp

shear-key resistance, friction and adherence show brittle failure and each shear deformation is tiny. Maximum dowel strength is associated with a certain amount of shear deformation along the interface.

In design of shear transfer elements, deformation characteristics are also very important as well as the strength. Our basis of shear transfer is the strength and deformation of concrete connections, and thinks that it is necessary to systematize the designing method by the theoretical model.

The research aims at the following: (1) Extraction and modeling of the shear transfer elements in concrete connections, (2) Proposal of the additional method of the various resistance elements satisfied with the condition of the shear deformation, (3) Verification by the structural experiment.

TEST PROGRAM

Specimens

The list of specimen parameters is shown in Table 1. The dimensions of specimens are shown Figure 1.

The specimens used for investigation of the shear transfer mechanism consisted of two concrete blocks. The dimensions and reinforcement details of all the specimens were identical: the width of 900 mm, the height of 1400 mm, and the thickness of 225 mm with an interface of 860 mm × 225 mm at the height of 700mm from the base.

The following parameters were investigated: (a) the kind of shear resistance in concrete connections [friction with axial force, dowel bar, shear-key, and compound of various elements], (b) the direct force acting transverse to the concrete interface [N = 0, 1500, -220 kN].

Combinations of parameters for all 10 specimens are given in Table 1.

The joint steel bars are used 2-D22 (ϕ= 22 mm, deformed bar). The shear-key is used in the central part of a concrete interface, and the height is h_{ck} = 30 mm, the length is L_{ck} = 240 mm and the width is t_{ck} = 225 mm. Since the form ratio of a shear-key (h_{ck} / L_{ck}) is 1/8, the shear-key shows compressive failure mode.

Table 1 List of specimen parameters

No.	Axial force (kN)	Shear resistance		
		Friction	Dowel	Sear-key
RF01	Variable*1	Yes	No	No
RF02	0	No	No	Yes
RF03	1500	Yes	No	Yes
RF04	0	No	Yes	No
RF05	1500	Yes	Yes	No
RF06	-220	No	Yes	No
RF07	Variable*2	Yes	Yes*3	No
RF08	0	No	Yes	Yes
RF09	1500	Yes	Yes	Yes
RF10	-220	No	Yes	Yes

*1) 250,500,750,1000,1250,1500,1750,2000kN
*2) positive loading: -220kN,
Negative loading: 100, 750, 1500kN
*3) High yield stress of joint bars

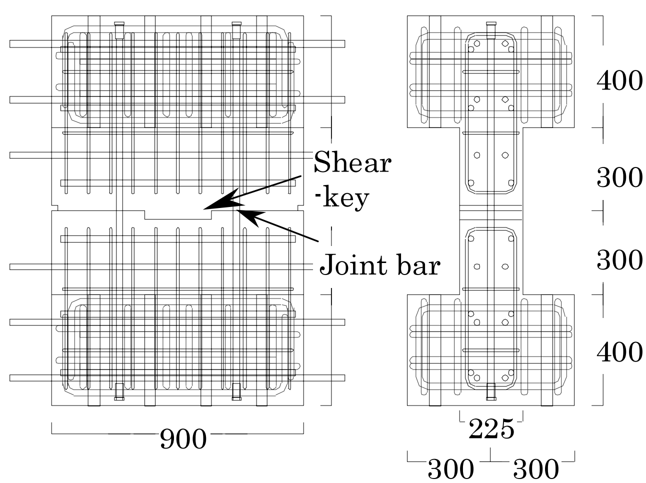


Figure 1 Dimensions of specimens

The lower section in the Figure 1 was cast first using a steel form at the interface. The upper section was cast five days later. The steel form was removed before connecting two concrete blocks and the interface was filled with grease. Thus, adherence of concrete surfaces was eliminated and shear force could be transferred by means of dowel bars, concrete shear-key, and friction with the axial force.

Mechanical properties of concrete and joint steel bar are shown in Table 2.

Table 2 Mechanical properties of materials

Concrete	σ_B *1 (N/mm^2)	σ_t *2 (N/mm^2)	E_c *3 (kN/mm^2)	Steel bar (D22)	σ_y *4 (N/mm^2)	Es *5 (kN/mm^2)	σ_u *6 (N/mm^2)
Upper	31.1	2.79	28.1	Normal	380	180	592
Lower	66.7	3.77	35.0	High	735	198	897
Average	**48.9**	**3.28**	**31.6**				

*1 σ_B: compressive strength, *2 σ_t: splitting strength, *3 E_c: elastic modulus
*4 σ_y: yield strength, *5 E_s: elastic modulus, *6 σ_u: tensile strength

Testing Arrangements

The concrete interfaces of specimens were subjected to cyclic shear forces and constant axial forces, using the loading apparatus shown in Figure 2. The loading direction was reversed at the horizontal displacement amplitudes of 3, 6, 9 mm, which was measured at the height of 30 mm from the concrete interface.

The location of displacement gauges and strain gauges of dowel bars are shown in Figure 3.

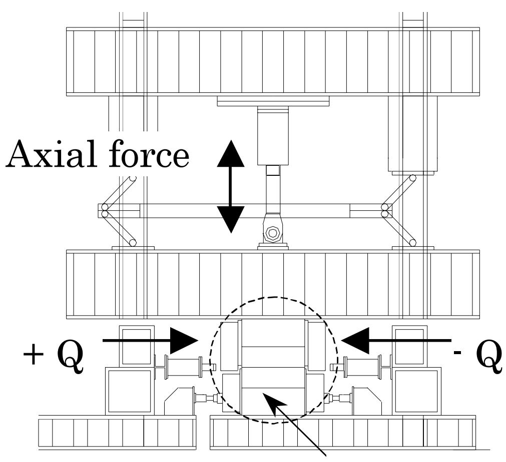


Figure 2 Loading apparatus

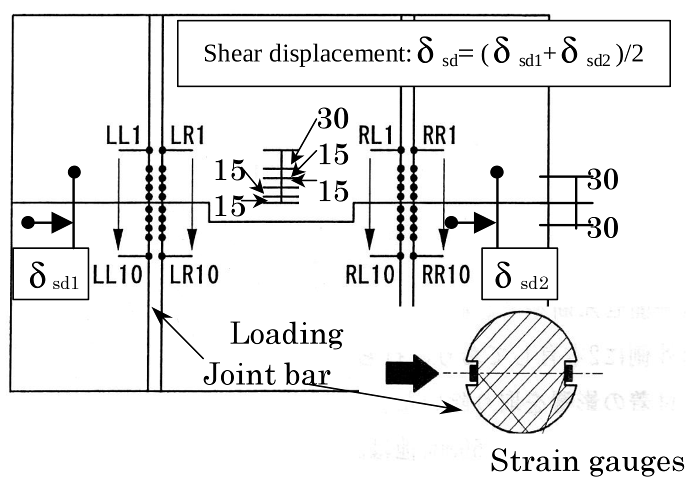


Figure 3 Measuring devices for dowel bars

TEST RESULTS

Friction with Axial force

The typical hysteresis relation of the shear force (Q) of the friction with axial force and the shear displacement (δ_{sd}) are shown in Figure 4, and the relation of the frictional shear force (Q_f) and the axial force (N) are shown in Figure 5.

RF01 was investigated to get the relation of friction and compressive axial force. It was measured on the compressive axial force level of eight stages [N = 250, 500, 750, 1000, 1250, 1500, 1750, 2000 kN] using the same specimen.

The friction with axial force can roughly be evaluated from the hysteresis loop as follows: (a) Q_f can be estimated from the first positive maximum strengths of the specimens under different axial force levels, and the force is proportional to the axial force. (b) The friction with axial force under cyclic loading may be taken at the flat level during reloading to the opposite direction until it meets the original displacement.

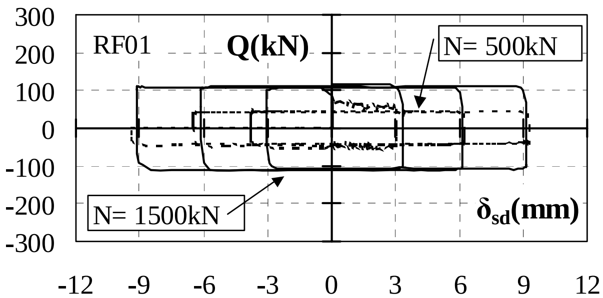


Figure 4 Typical curves of frictional force vs. shear displacement

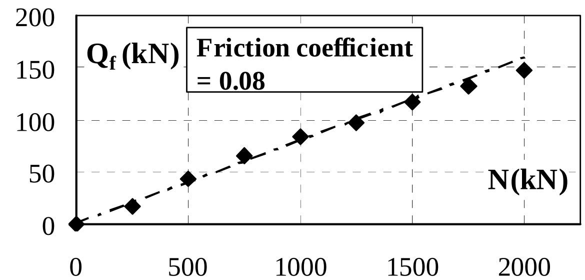


Figure 5 Influence of axial force on frictional force

Dowel Action

The typical hysteresis relation of the shear force (Q) of a dowel action and the shear displacement (δ_{sd}) are shown in Figure 6.

RF04 was subjected to the shear force and without the compressive axial force. Thus, the shear force could be transferred only by means of dowel action of the two deformed bars crossing the interface.

The dowel action can roughly be evaluated from the hysteresis loop as follows: (a) Substantial stiffness decreases gradually. (b) The maximum shear displacement with cycling increases. (c) The pinching effect is very pronounced, and the area of hysteresis loops with cycling decreases.

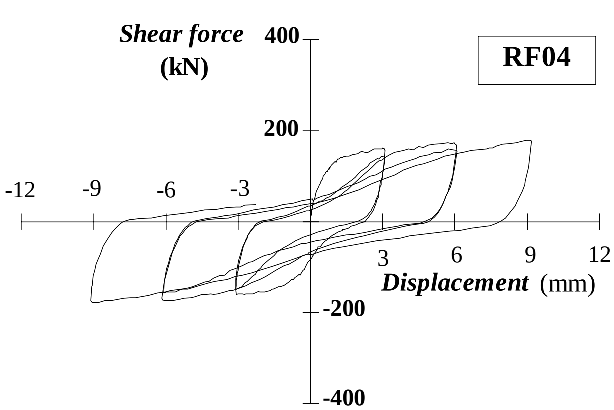


Figure 6 Typical curves of dowel force vs. shear displacement

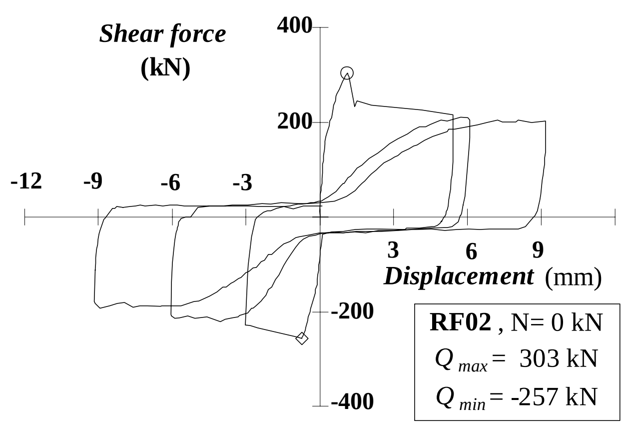
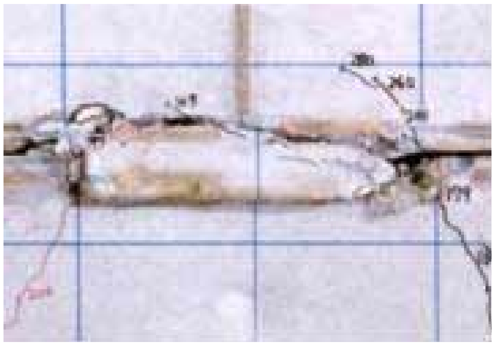
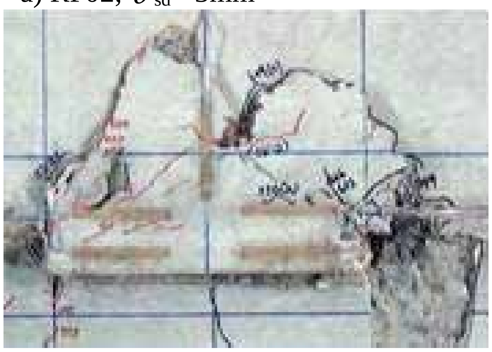


Figure 7 Typical curves of shear-key resistance vs. shear displacement

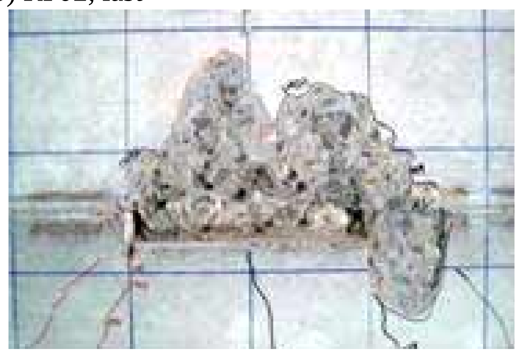


a) RF02, δ_{sd}= 3mm

b) RF02, last



c) RF03, δ_{sd}= 3mm



d) RF03, last

Photo.1 Failure conditions of Shear-key

Direct Shear Resistance of Concrete Shear-key

The typical hysteresis relation of the shear force (*Q*) of a shear-key resistance and the shear displacement (δ_{sd}) is shown in Figure 7, and the failure conditions of specimens are shown in Photo 1.

RF02 subjected to the shear force and without the compressive axial force. Thus, the shear force could be transferred only by means of shear-key resistance. RF02 showed compressive failure of shear-key. The stiffness of the hysteresis loop is high and the displacement of that is minimal until the compressive failure of shear-key. The resistance after compressive failure is constant.

Compound Effect of Shear Resistances with Different Hysteresises

The hystereris relations between the shear force and the shear displacement are shown in Figure 8. The relations of the total shear force and the shear displacement are shown with dotted lines. The total shear force combines each shear resistance at the same shear displacement.

Combination of dowel and shear-key

RF08 is the combination of the shear-key and the dowel action. And the hysteresis loop of RF08 is the compound hysteresis loop (RF02+RF04) of the shear-key (RF02) and the dowel action (RF04) shown with the dotted line. RF08 and RF02 showed compressive failure of the shear-key in the first positive and negative loading.

The positive and negative shear capacities of (RF02+ RF04) are almost equal to the capacity of RF08. The enveloped curves of hysteresis loops between RF08 and (RF02+RF04) show almost equal behavior. However, the pinching effect of RF08 is pronounced, and decreases the area of histeresis loop with cycling.

Combination of dowel and friction

RF05 and RF06 are the combination of the dowel action and the friction with the axial force. RF05 was subjected to the compressive axial force +1500kN, and RF06 was subjected to tensile axial force –220kN.

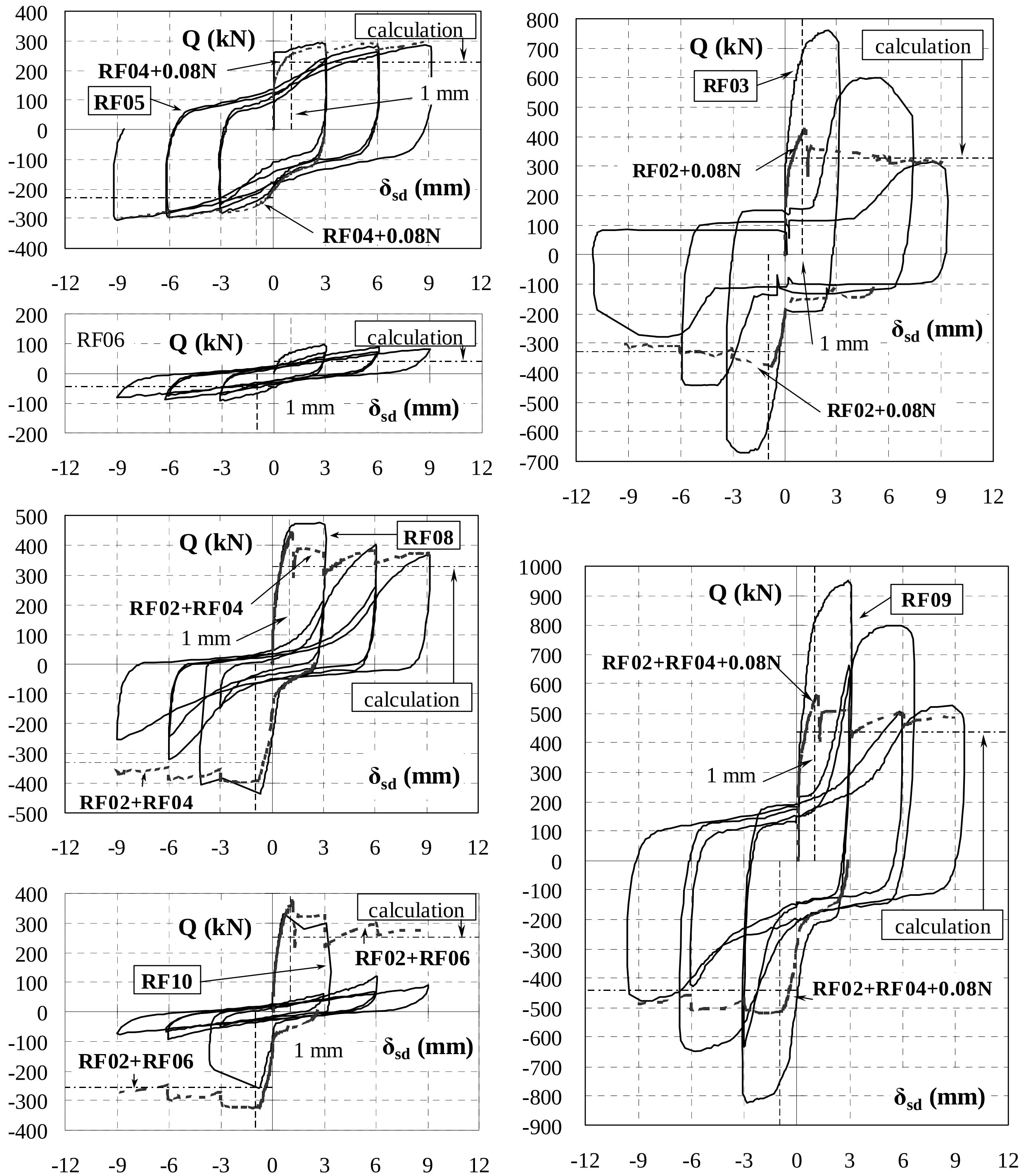


Figure 8 Hysteresis curves of mean values of Total force
(dowel resistance or the shear-key resistance with axial force) vs. Shear displacement

Therefore, although the friction occurs in the interface of RF05, the friction does not occur in the interface of RF06. The hysteresis loop of RF05 is the compound hysteresis loop (RF01+ RF04) of the dowel action (RF04) and the friction with the compressive axial force (RF01) shown with the dotted line. The hysterisis loops between RF05 and (RF01+ RF04) show almost equal behavior. However, the shear displacement occurred suddenly in the first loading of RF05, and the shear force was larger than that of (RF01+RF04).

Combination of shear-key and friction

RF03 and RF10 are the combination of the shear-key and the friction with the compressive axial force. RF03 was subjected to compressive axial force +1500kN, and RF10 was subjected to tensile axial force –220kN. Although the friction occurs in the interface of RF03, the friction does not occur in the interface of RF10.

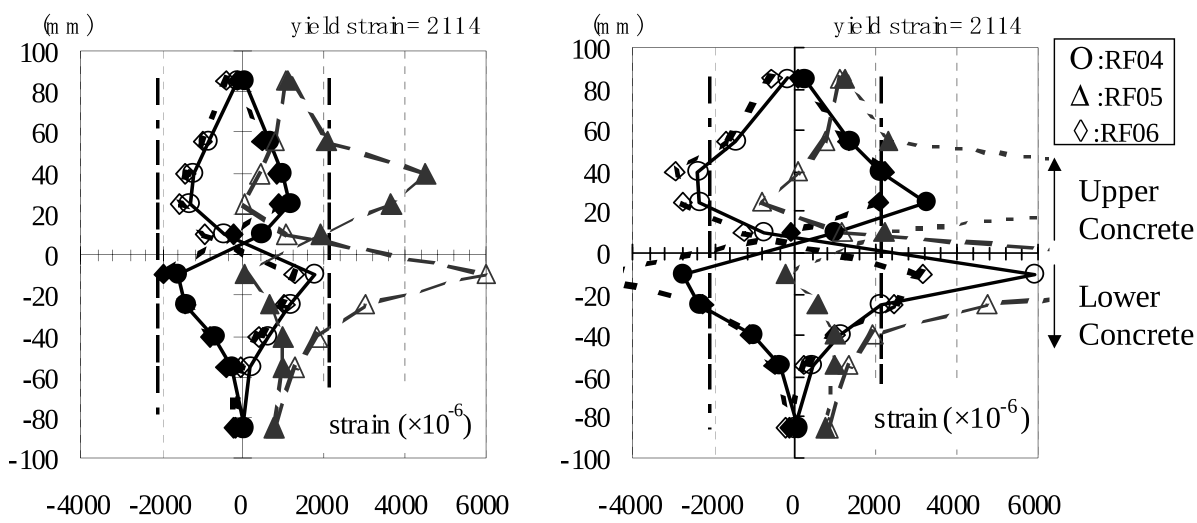
The hysteresis loop of RF03 is the compound hysteresis loop (RF01+ RF02) of the shear-key (RF02) and the friction with axial force (RF01) shown with the dotted line. RF03 and RF10 showed compressive failure of the shear-key in the first positive and negative loading. The positive and negative shear capacities of RF03 are larger than the capacity of (RF01+RF02) about 80%.

DISCUSSION

Strain distribution of Joint bars

Strain distributions of RF04, RF05 and RF06 to investigate the dowel action at the same shear displacement (δ_{sd} = 0.5, 1 mm) are shown in Figure 9.

The configurations of the front reverse sides are symmetrical to the loading direction, and the shear force is resisted due to bending of the joint bars locally. Also, those configurations are equal regardless of the axial force levels subjected, but the strain levels with tensile force are different. The characteristics of such a strain distribution are similarly observed in RF08, RF09 and RF10 to investigate the compound effects of dowel action and shear-key resistance.



a) δ_{sd} = 0.5 mm b) δ_{sd} = 1.0 mm

Figure 9 Strain distributions of specimens to investigate the dowel action

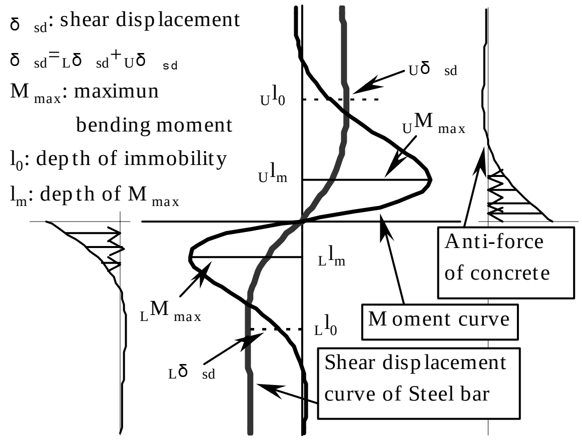


Figure 10 Dowel mechanism

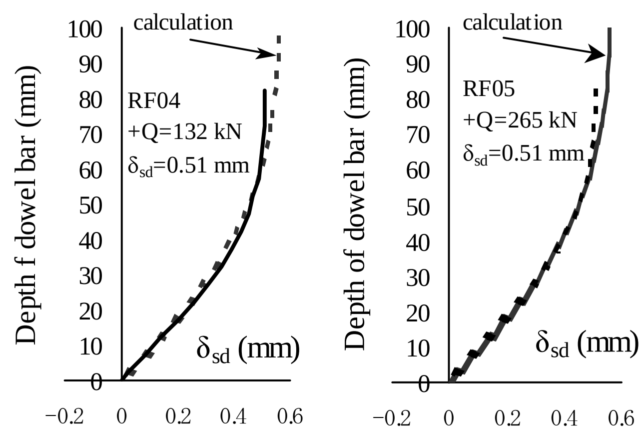


Figure 11 Shear displacement of Dowel bar

Dowel Mechanism

Referring to the dowel mechanism shown in Figure 10, the external shear force tends to produce slippage along the interface. It is thought that the dowel bar is subjected to the bending moment from the concrete for an anti-force. The anti-force per unit length is expressed with Equation 1. It assumes that the anti-force coefficient is fixed in the depth of concrete, and the basic equation to calculate the bending displacement of the dowel bar will be given by Equation 2.

$$ {}_i p_s(x) = {}_i k_c \cdot B \cdot y \qquad \text{(Eq. 1)} $$

$$ E_s I_s \frac{d^4 y}{dx^4} + {}_i k_c \cdot B \cdot y = 0 \qquad \text{(Eq. 2)} $$

The variables are defined as:
x : Depth of the dowel bar from the interface (mm).
y : Horizontal displacement of the dowel bar in the depth x (mm).
E_s : Modulus of elasticity of the dowel bar (N/mm^2).
I_s : Geometrical moment of inertia (mm^4).
${}_i p_s(x)$: Horizontal anti-force of the concrete in the depth x (N/mm).
B : Diameter of the dowel bar (mm).

${}_i k_c$: Coefficient of concrete anti-force (N/mm^3)[${}_i k_c = 55\left(\frac{{}_i E_c \cdot {}_i \sigma_B}{E_s \cdot {}_i \delta_{sd}}\right)^{\frac{3}{4}}$].

${}_i E_c$: Modulus of elasticity of concrete (N/mm^2).
${}_i \sigma_B$: compressive strength of concrete (N/mm^2).
${}_i \delta_{sd}$: shear displacement on concrete surface (mm).

For the calculation of dowel strength, it is assumed that the dowel behaves like a horizontally loaded free-headed pile embedded in a cohesive soil and that yielding of the bar and crushing of the concrete occur simultaneously.

In the interface, the shear force of the opposite direction is loaded [the absolute value] mutually equally. Therefore, the dowel bar in depth 0 mm from the interface is subjected to a shear force (Q = -q), and is not subjected to a bending moment (M = 0). Moreover, when ${}_i k_c$ is assumed to be fixed, and a dowel bar is assumed to be an elastic material, and the theoretical solution of Equation 2 is calculated, it can be expressed with the following equations.

$$y = \frac{q}{2E_s \cdot I_s \cdot {}_i\beta^3} e^{-{}_i\beta x} \cos{}_i \beta x \qquad \text{(Eq. 3)}$$

$$M = \frac{q}{\beta} e^{-{}_i\beta x} \sin{}_i \beta x \qquad \text{(Eq. 4)}$$

$$M_{\max} = -\frac{q}{{}_i\beta} e^{-\frac{\pi}{4}} \cdot \sin\frac{\pi}{4} = -0.3224 \frac{q}{{}_i\beta} \qquad \text{(Eq. 5)}$$

Where:

$${}_i\beta = \sqrt[4]{\frac{{}_ik_c \cdot B}{4E_s \cdot I_s}} \text{ , } l_m = \frac{\pi}{4{}_i\beta} \text{ , } l_0 = \frac{3\pi}{4{}_i\beta}$$

M_{max} : Maximum bending moment of the dowel bar (N•mm),
l_m : Depth of M_{max} (mm), l_0 : Depth of immobility (mm)

In general, where the dowel is simultaneously subjected to a tensile stress $\sigma_s = \alpha \cdot \sigma_y$ ($\alpha \leq 1.0$), the plastic moment of the bar decreases.

$$M_{pl} = \frac{d^3 \cdot \sigma_y \left(1 - \alpha^2\right)}{6} \qquad \text{(Eq. 6)}$$

Thus, the dowel strength is calculated by Equation 7 ($M_{max} = M_{pl}$).

$$Q_{dwl} = \frac{d^3 \cdot \sigma_y \left(1 - \alpha^2\right) {}_i\beta}{1.934} \qquad \text{(Eq. 7)}$$

Shear-displacement distributions of the dowel bars in the upper concrete of RF04 and RF05 are shown in Figure 11. The calculations are integrated twice with the strain distributions shown in Figure 9. The calculations agree well with the measurements. Therefore, it is thought that the proposed dowel mechanism is appropriate.

Total method of various shearing resistance forces

Monotonic hysterisis relations per one dowel resistance (q_{dwl}) and shear displacement are shown in Figure 12. The curves (RF04 and RF05) measured by the experiment are solid lines and the curve calculated from the Equation 3 is shown by the dotted line.

The dowel resistance of RF05 subtracts the calculated friction with axial force from the measured total shear force. The calculation evaluates the measurement of RF04 without the compressive axial force appropriately. The shear displacement of RF05 occurs suddenly, and the calculation evaluates the measurement to be a little larger. This seems to be an influence of the adherence of concrete surface.

Monotonic hysterisis relations per one shear-key (q_{ck}) and shear displacement are shown in Figure 13. The shear-keys of RF03 and RF09 subtract the calculated frictions with axial force from the measured total shear forces, and also the shear-keys of RF08 and RF09 subtract the calculated dowel resistances from the measured total shear forces. The hysterisis curves of the shear-keys with the same compressive axial force level show as almost equal.

These figures lead to the following: (a) Total shear resistance can be evaluated as the sum total of each shear transfer element at the same shear displacement. (b) Dowel action is not influenced by compressive axial force. (c) Structural performance (resistance and stiffness) of shear-key increases by the compressive axial force. Referring to the dowel mechanism shown in Figure 10, the external shear force tends to produce slippage

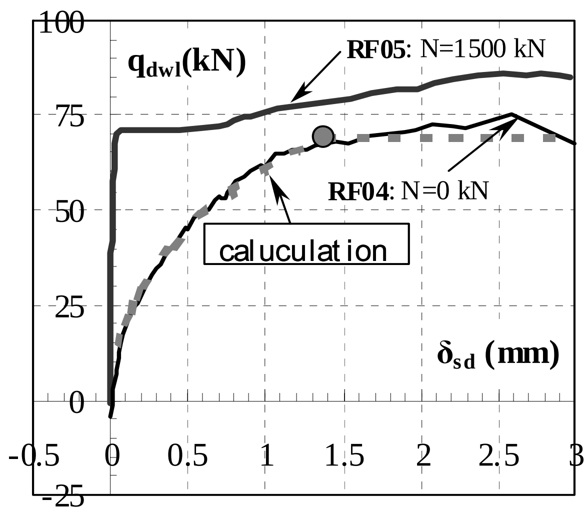


Figure 12 Monotonic hysterisis curves of Dowel action

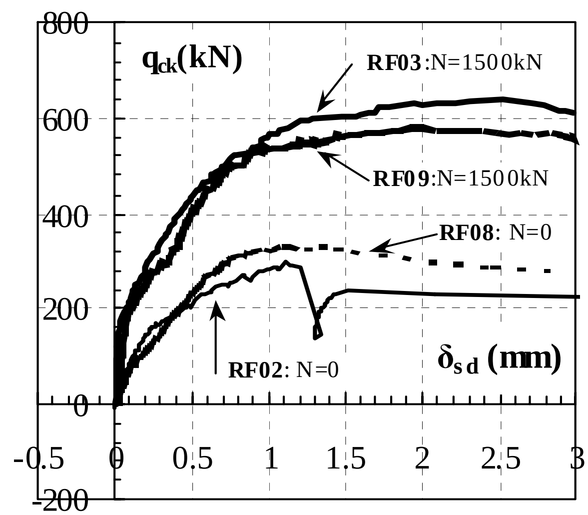


Figure 13 Monotonic hysterisis curves of Shear-key resistance

CONCLUSIONS

Basic experiments on concrete connections were conducted on the shear transfer and the shear displacement behaviour in concrete connections under shear and axial force. The following conclusions may be drawn.

(a) The shear transfer mechanism and shear displacement behavior in concrete connections is clarified. And the shear transfer mechanism is verified by the structural experiments.

(b) The shear transfer strength can be evaluated as the sum total of each shear transfer element at the same shear displacement. The evaluation equation is also proposed.

REFERENCES

1. Katsuhiko N, Yoshimasa H, Shigenori H, Yasuhiro M. “The compound effect of shear transfer elements in pre-cast concrete connections”. Transactions of the Japan Concrete Institute, Vol. 23, 2001: 435-442