PRECAST CONCRETE CONSTRUCTION SYSTEM OF FOOTING BEAMS FOR PRECAST CONCRETE WALLED STRUCTURES

Katsumi KOBAYASHI[1], Fumitaka IKADAI[2] And Yusaku ARAI[3]

SUMMARY

The construction of footing beams of PCa walled structure is coded to be monolithic reinforced concrete in Japan[1][3]. If they would be constructed by PCa system, however, the construction accuracy would be much improved and the high quality of construction could be secured. This paper describes R&D of PCa system of footing beams for PCa walled structures.

The partitioning of footing beams into PCa members, their joint detail, the structural design method and the construction procedure were discussed first. To investigate the structural performance of vertical joints and horizontal joints that would be used in the PCa system, the loading tests were conducted. The capacity, rigidity, crack pattern, etc. were compared with those of monolithic reinforced concrete footing beams.

Well satisfactory test results were obtained by adopting continuous box type shear keys, regarding the shear capacity, failure mode, load-deformation relation, etc. and they were mostly close to those of monolithic reinforced concrete. The dislocation of joint interface was proved to be negligible. The horizontal joint between footing beam and slab behaved perfectly as T-section. As a result, it was proved that the enough safety margins to the various limit states could be secured.

The PCa system for footing beams was successfully developed in this study to assure the enough structural safety. Two new apartment house buildings already completed where this system was introduced. The advantages of the PCa concrete construction system of footing beams were confirmed in the practical construction.

INTRODUCTION

The footing beams of PCa walled structure is coded to be constructed in monolithic reinforced concrete[1][3]. When the footing beams are constructed in site, however, it is quite difficult to keep the splicing sleeve joint bars at upright position. Sometimes they don't accurately meet the splicing sleeve embedded in the upper wall panels. This doesn't assure the quality of completed structures. If the footing beams would be constructed by PCa system shown in Fig.1, the construction accuracy would be much improved and the high quality of construction could be secured. In addition, the construction period and the construction cost would be reduced. The safety work of construction is also secured.

To employ PCa system for the footing beams in Japan, the almost equivalent structural performance to the monolithic reinforced concrete is required. This paper describes the development of PCa concrete construction system of footing beams, the structural design concept and the experimental results that would verify the structural performance of the system.

[1] *Dept of Architecture and Building Engineering, Fukui University, Fukui, Japan Email: katsumi@anc.anc-d.fukui-u.ac.jp*
[2] *Dept of Architecture and Building Engineering, Fukui University, Fukui, Japan Email:ikadai@anc.anc-d.fukui-u.ac.jp*
[3] *Technology Development Section, Kiuchi Corporation, Shizuoka, Japan Email: kaihatsu@kiuchi.co.jp*

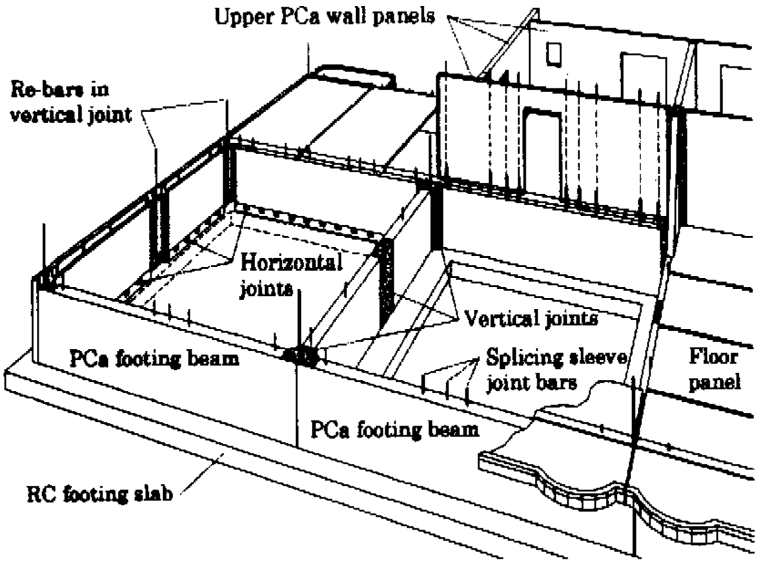

Fig. 1: PCa concrete construction system of footing beams for PCa walled structures

PCA SYSTEM FOR FOOTING BEAMS

Outline of the System

The outline of the system is illustrated in Fig.1. To be adjustable to any ground conditions, just the footing beams are produced in the factory as PCa members. The footing slabs are cast in site and horizontally jointed with the footing beams to perform T-section.

The partitioning of footing beams into PCa members is same as those of the upper structural wall panels. As a result, the vertical joints of footing beams come on the lower extension of the vertical joints of the upper structural wall panels as shown in Fig.2. The jointing region of footing beams performs almost shear panel zone. Here, the bending moment is not influential and the shear stress is dominant. By dividing the footing beams into the panel-shaped PCa members in the same way as the upper structural wall panels, the following advantages are found.

(1) The high quality concrete can be cast on the flat bed in the factory.

(2) The form work can be simplified.

(3) The footing beam can be stocked vertically and the area of stock space can be reduced.

(4) The transportation from the factory to the construction site can be done in the same way as that of upper structural wall panels.

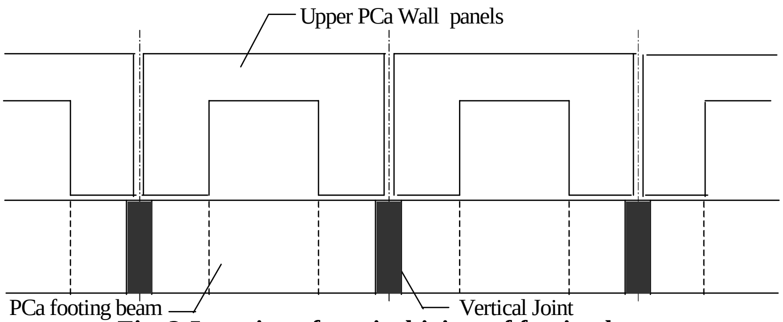

Fig. 2:Location of vertical joints of footing beams

Detail of Joints

The crossing of footing beams can be classified into four patterns, L, I, T and +. They are adjustable to any floor plans. In the L, I and + crossing patterns, the main bars of footing beams are spliced by welding. In the T crossing pattern, the main bars of orthogonal footing beam are anchored in the joint concrete, connecting the top and the bottom bars in U-shape.

To abbreviate the finishing on the side of footing beams that come on the outer perimeter of the plan, the jointing part of footing beams has the type-1 detail with outer concrete cover panel shown in Fig.3 (Left). That of the footing beams that are set inside the plan has the type-2 detail shown in Fig.3 (Right).

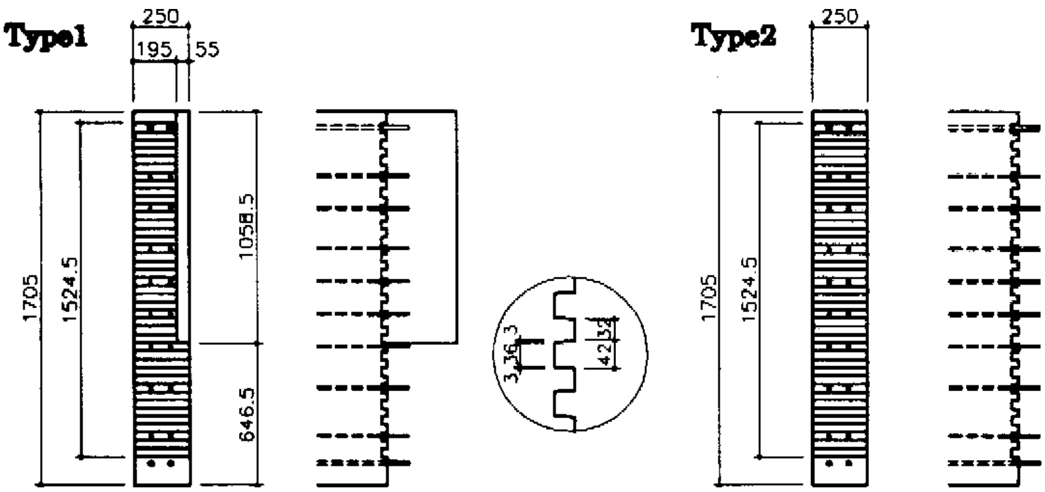

Fig. 3: Detail of vertical joints

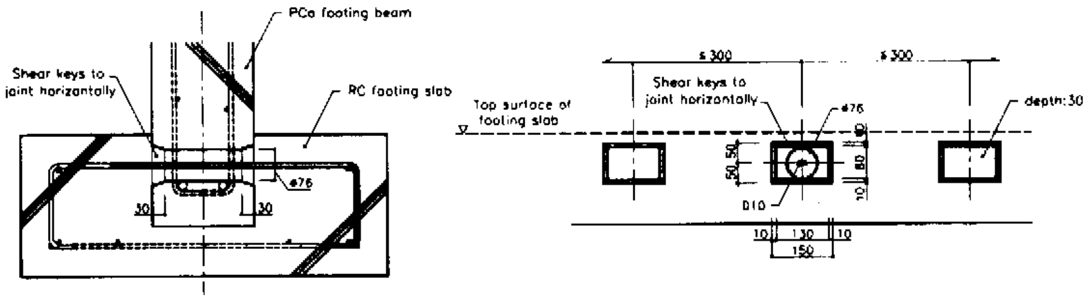

Fig. 4: Detail of horizontal joints

In the horizontal joint between footing beams and slabs, the box type shear keys with holes are made on both side of footing beams to joint horizontally with footing slabs. In addition, the tie bars are placed in the holes to tighten the interlocking of shear keys as shown in Fig.4. This assures the shear force and axial force transfer from footing beams to slabs.

Construction Procedure

Figure 5 shows a typical construction procedure by this system developed by the authors.
(1) After excavation, the foundation base is prepared using the broken stones and the leveling concrete.
(2) PCa footing beams is set at the scheduled position adjusting the level by chain-block. Then, they are temporally fixed by PC-support.
(3) The main bars of footing beams and the tie bars for shear keys are spliced by welding in the vertical joints. And required reinforcing arrangement is done in the joints and in the slabs.
(4) The standardized forms are installed to the jointing parts of the footing beams and the footing slabs. Then, the concrete is placed.
(5) The upper structural wall panels and the floor panels are set and jointed.

By this PCa system for footing beams, the construction accuracy is much improved, and the construction work can be done by the less variety of workmanship. And the construction site control can be simplified. This leads to the cost reduction, and also the construction period can be reduced by almost half comparing with the ordinal construction procedure.

REQUIREMENTS FOR VERTICAL JOINTS

When any PCa system is introduced, the building law in Japan requires the equivalent structural performance to the monolithic reinforced concrete. And also the ultimate strength design is required to the joints of PCa members. In this study, the following structural performances were verified by the loading tests, and the structural design procedure for the vertical joint of upper structural wall panels was adopted.
(1) The footing beam with vertical joint has the same shear force-relative displacement relation till short-term design load as that of the monolithic RC footing beams.

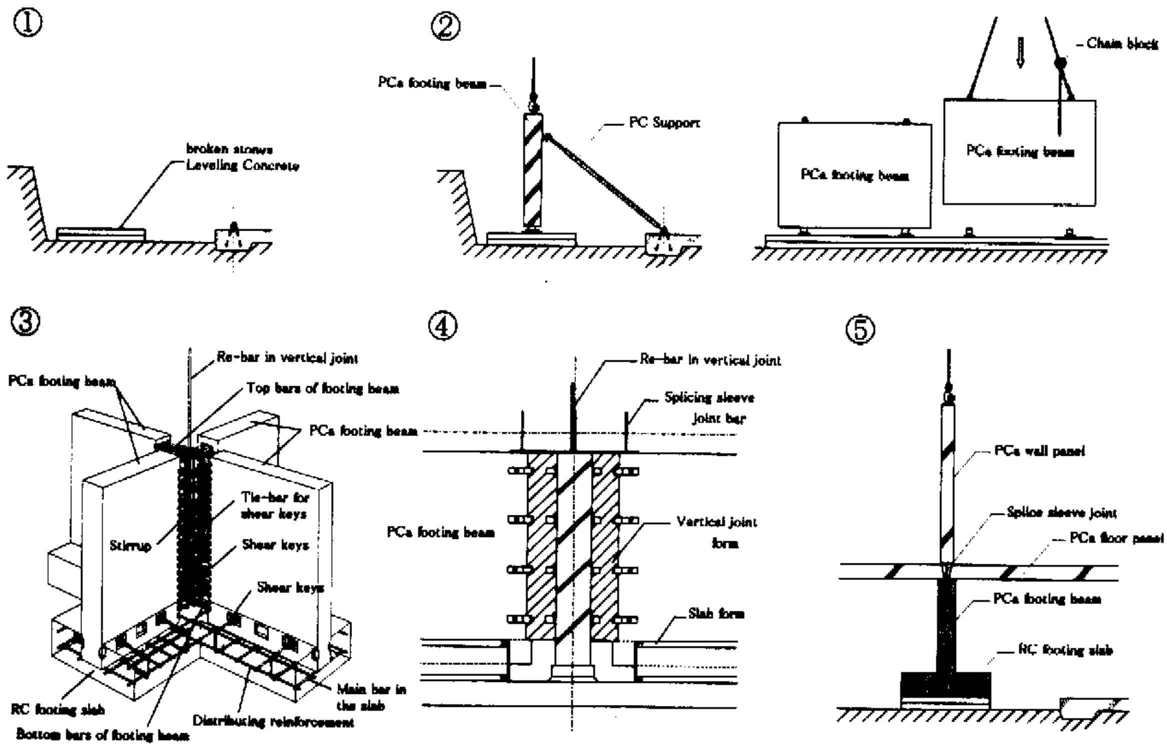

Fig. 5: Typical Construction Procedure by PCa system for footing beams

(2) The footing beam with vertical joint has higher shear capacity than the ultimate state design load.
(3) The relaxation of shear keys interlocking does not occur so much in the vertical joint till short-term design load.

The footing slabs are not expected to contribute to the increase of shear capacity of footing beams. The role of footing slabs is to transfer the axial force and the horizontal force to the ground uniformly.

VERTICAL JOINT OF FOOTING BEAMS

Experimental Program:

The main objective of this experiment is to decide the detail of shear keys. The parameters were the shape, the number and the depth of shear keys. As shown in Fig.6, the box type shear keys are same as those used in the vertical joints of the upper structural wall panels. They are compression failure type shear keys mechanically. The folded plate type shear keys were expected the easiness of form work in the factory. When the depth and the number of box-type shear keys are increased, they transformed into the continuous-box-type and they are shear-off failure type shear keys mechanically. The geometry of test specimens simulating the footing beam illustrated

Table 1:Test specimens for vertical Joints

Specimen's Name	Main bars (SD345)	Shear Reinforcement (SWM-P)	Shear Keys				Concrete strength (MPa)
			Shape	Number	Depth(mm)	Tie bars	
AS-0	3-D13 (0.753%)	6-4.5ϕ (0.339%)	No vertical joint				Joint: 28.5 Beam: 20.2
AS-1			Folded	3		6-4.5ϕ	
AS-2				4		8-4.5ϕ	
AS-3				3		6-6.0ϕ	
AS-4			Box	3	11.7	6-4.5ϕ	
AS-5				4	11.7	8-4.5ϕ	
AS-10	3-D13 (0.734%)	7-6.0ϕ (0.703%)	No vertical joint				Joint: 22.4 Beam: 17.4
AS-11			Box	3	16.8	6-4.5ϕ	
AS-12				4	16.8	8-4.5ϕ	
AS-13				Continuous	15.0	8-4.5ϕ	

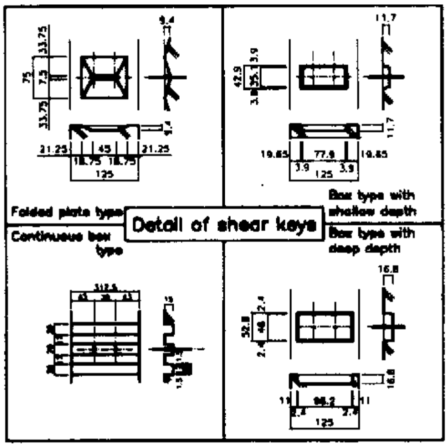

Fig. 6: Discussed shear key types

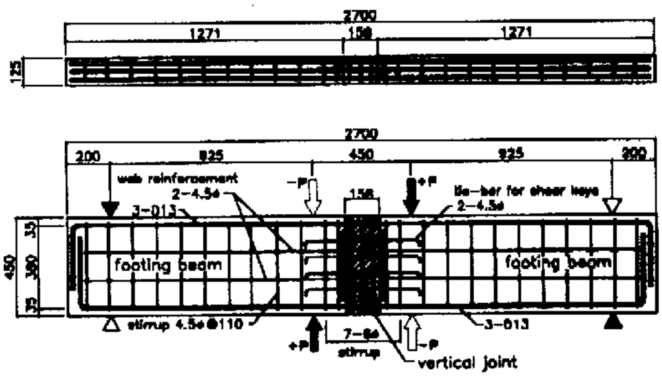

Fig. 7: Geometry of test specimen for vertical joint

in Fig.2 is shown in Fig.7 and all the specimens are listed in Table 1.
The specimens were tested under the anti-symmetric bending moment condition. The shear span to depth ratio is 0.56. The relative vertical displacement between the loading points (δ) was measured by electric transducers. The horizontal separation and the vertical movement of shear key interlocking were also measured by Ω-type electric transducers. Each specimen was given the reversed cyclic loads with increase of loading stress level considering the structural design load.

Test Results:

The shear force(Q) and relative displacement(δ) relations are shown in Fig.8 and Fig.9. The stiffness of the specimen with folded plate type shear keys degraded at early stage and was not acceptable. The specimen with box-type shear keys showed better performance. From Fig.8, it was found that the stiffness of specimens with more number of box type shear keys has the closer performance to that of the monolithic specimen. No difference was found in the Q-δ relation of the specimen with continuous box type shear keys and the monolithic specimen. Figure 9 shows the depth of shear keys much improves the Q-δ relations of PCa specimens so that they come close to the monolithic specimen. The specimen with continuous box type shear keys has almost same shear capacity and shear failure mode as those of monolithic specimen. Table 2 shows that
the large safety margin can be assured when the design concept for the vertical joints of upper structural wall panels would be applied to the design of vertical joint of footing beams.
In the specimen with continuous box type shear keys, the horizontal separation and the vertical movement of shear key interlocking were 0.02mm and 0.006mm respectively at the short-term design shear force of vertical joint. Even at the short-term allowable shear force level as a beam by AIJ standard[2], they were 0.16mm and 0.27mm respectively.

Table 2: Safety margin of verified shear force in structural design

Specimen's Name	Shear capacity(kN)			Verified shear force in design				Remarks
	Q_{max}	Q_{SU}	Q_{max}/Q_{SU}	$_RQ$	Q_{VU}	$Q_{max}/_RQ$	Q_{max}/Q_{VU}	
AS-0	248	207	1.20					monolithic
AS-4	191		0.92	47.2	94.5	4.05	2.02	box, shallow, 3
AS-5	202		0.98	63.0	126.4	3.20	1.60	box, shallow, 3
AS-10	244	233	1.05					monolithic
AS-11	218		0.93	83.5	130.3	2.61	1.67	box, deep, 3
AS-12	245		1.05	111.7	174.4	2.20	1.40	box, deep,4
AS-13	270		1.16	39.2	103.9	6.90	2.60	box, continuous

Q_{max}: Maximum shear force in the experiment
Q_{SU}: Calculated shear capacity of footing beam[2]
$_RQ$: Short-term allowable shear force of vertical joint when the structural design procedure for the vertical joints of upper wall panels is introduced.[1]
Q_{VU}: Evaluation of ultimate shear force of vertical joint when the structural design procedure for the vertical joints of upper wall panels is introduced.[1]

As a result, the continuous box type shear keys are mostly acceptable and the jointed footing beams show almost no difference from the monolithic one. The authors decided to employ the continuous box type shear keys for the vertical joints of PCa footing beams.

PERFORMANCE OF VERTICAL JOINT ON THE PILE FOUNDATION

Outline of Experiment:

When the structure is constructed on the pile foundation, the footing beam would be twisted because of the eccentric location of piles due to the construction error. As a result of investigation of construction records in the past, the maximum eccentric distance was proved to be less than 200mm. Assuming 20cm of eccentric distance and the capacity of piles, the torsional shear stress was calculated to be 0.4 MPa. Four specimens with continuous box type shear keys in Table 3 were tested. The parameter is the torsional shear stress level. DS-0 is the monolithic specimen without vertical joint.

The loading idea is illustrated in Fig.10. The steel arms were installed on both side of footing beam and the torsional moment was generated by attaching some dead weight at the tips of steel arms. Then, the reversed cyclic loads were given in the same way as that of the previous section.

Table 3:Test specimens

Specimen Name	Main bars (SD345)	Shear Reinforce-ment (SWM-P)	Shear Keys Shape	Number	Depth	Tie bars	Torsional Shear Stress (MPa)	Concrete strength(MPa)
DS-0	3-D13 (0.734%)	7-6.0ϕ (0.703%)	No vertical joint				0.0	Joint: 23.1 Beam: 26.7
DS-1			Box	Continuous	15.0mm	8-4.5ϕ	0.0	
DS-2							0.4	Joint: 26.6 Beam: 29.7
DS-3							0.8	

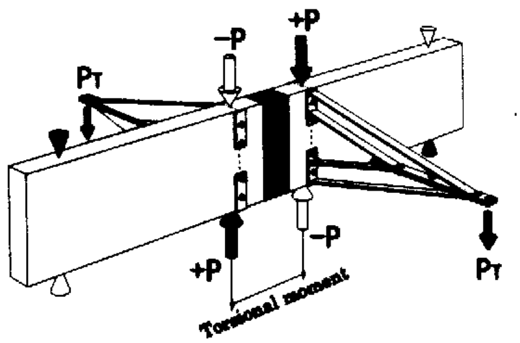

Fig. 10: Loading system under torsional moment

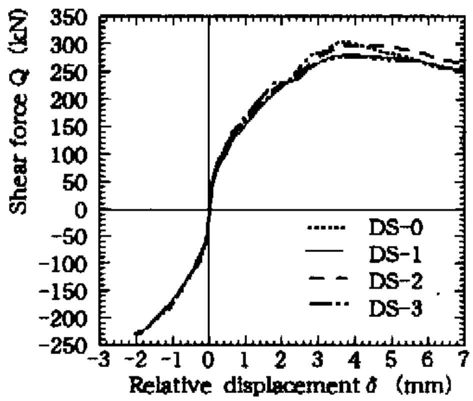

Fig. 11: Q-δ relations

5.2 Test results:

The applied shear force (Q) and the relative displacement (δ) relations are shown in Fig.11. The affect of torsional shear stress was not seen. Also, no differences of failure mode, cracking pattern, movements of shear keys, etc. was observed in comparison with the specimen without the tosional moment. As a result, it would be not necessary to take account the eccentric location of piles into consideration in the structural calculation of vertical joint of footing beams.

HORIZONTAL JOINT BETWEEN FOOTING BEAM AND SLAB

Experimental Program:

The geometry and the detail of specimens are shown in Fig.12. To expect the uniform reaction force distribution on the bottom of footing slab, the rigidity of the connected T-section is needed. For this purpose, the box type shear keys were made on both sides of footing beams. The number of shear keys was decided so that they could fully transfer the vertical load to the slab through the shear keys.

Seven specimens listed in Table 4 were tested. First four specimens were tested by two points cyclic loading, keeping the slab side in tension. When the footing slab receives the reaction force directly from the ground, the footing slab is in compression side. The evaluation of the rigidity of T-section, however, will be able to be done more easily when the footing slab is apart from the neutral axis to the tension side.
The last three specimens were tested under the anti-symmetric bending moment condition to investigate if the connected T-section keeps the rigidity of monolithic T-section during an earthquake.

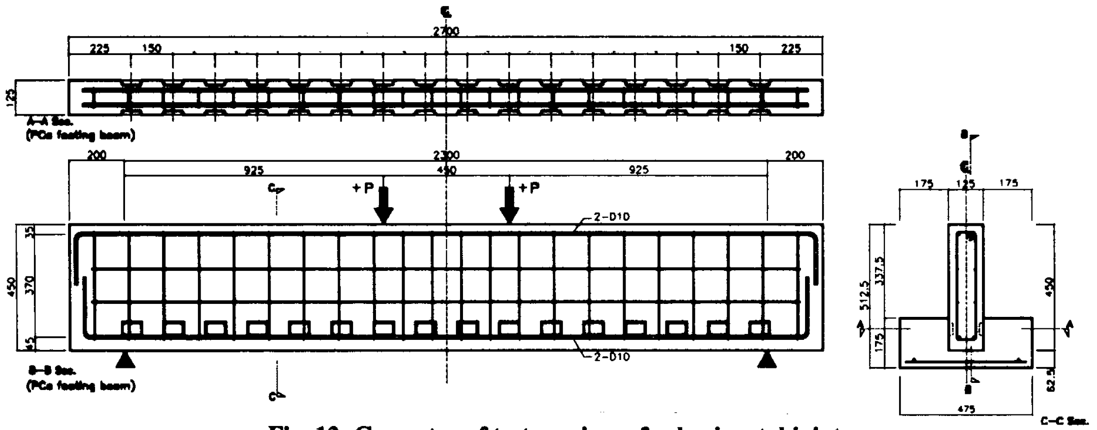

Fig. 12: Geometry of test specimen for horizontal joint

Table 4:Test specimens for horizontal joints

Specimen's Name	Footing Beams Main bars (SD345)	Footing Beams Shear Rein-forcement (SWM-P)	Footing slabs Main bars (SD345)	Footing slabs Distributing Reinforcement (SWM-P)	Shear keys Shape	Shear keys Depth(mm)	Shear keys Tie bars	Concrete strength (MPa)
BM-0	2-D10 (0.276%)	4-4.5ϕ (0.226%)	2-D10	4.5ϕ@200	No horizontal joint			Beam: 24.4 Slab: 28.0
BM-1					Box	16.8	No bars	
BM-2							D6@150	
BM-3							D10@450	
BS-0	2-D10 (0.276%)	4-4.5ϕ (0.226%)	2-D10	4.5ϕ@200	No horizontal joint			Beam: 21.2 Slab:23.3
BS-1					Box	16.8	D6@300	
BS-2							D6@150	

6.2 Test Results:

The applied load (P) and the deflection (δ) relations of BM-0 to BM-3 are shown in Fig.13. All the specimens have almost same P-δ relations. Even after yielding, the stiffness of the connected T-section did not degrade in comparison with the monolithic specimen. The flexural capacity of BM-2 and BM-3 was a bit higher, because the additional bars to keep the position of tie-bars for shear keys worked as tensile reinforcements.

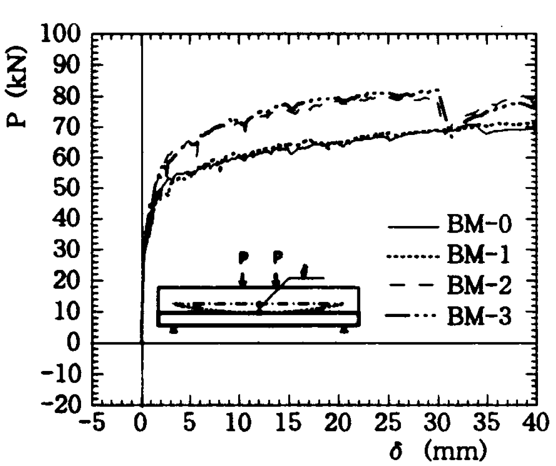

Fig. 13: Q-δ relations for BM-0 to BM-3

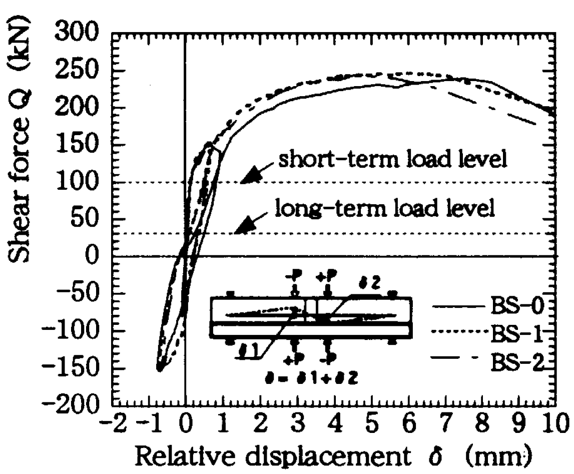

Fig. 14: Q-δ relations for BS-0 to BS-2

The applied load (P) and the relative displacement (δ) relations of BS-0 to BS-2 are shown in Fig.14. Even under the reversed cyclic bending moment and shear force, the stiffness of the connected T-section did not degrade till ultimate state. The separation of footing slabs from the beams at the horizontal joint was not measured at the short-term design shear force level and 0.016mm even at the ultimate state.

As a result, the box type shear keys that were made on both sides of footing beams worked very well. And it was proved that the footing slabs have enough rigidity to receive the uniform reaction force distribution from the ground. The stiffness of the connected T-section would not degrade even during an earthquake.

CONCLUSION REMARKS

1. Using continuous box type shear keys, regarding the ultimate shear capacity, failure mode, load-deformation relation, etc. which were mostly close to those of monolithic reinforced concrete footing beam. The dislocation of joint interface was proved to be negligible.
2. The horizontal joint between footing beam and slab behaved perfectly same as the monolithic reinforced concrete beams with T-section.
3. When the system is constructed on the pile foundation, the affect of eccentric location of piles can be neglected in the structural design of vertical joint of footing beams.
4. The enough safety margin to the various limit states can be secured, when the design procedure of the vertical joint of PCa upper structural wall panels is applied to the design of the vertical joint of PCa footing beams.
5. The joint detail of PCa footing beams was successfully developed in this study to assure the enough structural safety. Two new apartment house buildings already completed that have the PCa footing beams developed in this study. The advantages of the PCa concrete construction system of footing beams were confirmed in the practical construction.

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