THE JAPAN PRESSS PRECAST CONCRETE CONNECTION DESIGN

Hitoshi SHIOHARA[1] And Fumio WATANABE[2]

SUMMARY

A four-year US-Japan cooperative research program on earthquake resistant design of precast concrete structure had started on 1988. It aimed development of a precast concrete seismic structural system (PRESSS). In the Japan-PRESSS program, a connection design manual for moment resisting frame building was developed as a part of the program. This paper outlines the design manual and introduce the state-of-the-art on the seismic design for precast concrete connections in Japan. It features connection design based on the performance of connections. Performance demand on con-nections are that they shall be of equivalent monolithic similar to ordinary cast-in-place R/C mem-ber. The adopted definitions of equivalent monolithic are (1) connections have stiffness such that the member design stress could be predicted with enough accuracy by structural analyses applied to monolithic cast-in-place concrete structural system, (2) connections have equal to or larger strength such than it could transfer force occurring in member or between members, (3) members with con-nections have restoring force characteristics by which no significant difference in earthquake response occur, and (4) connection should have equivalent to or superior serviceability, durability and fire safety. For the detailing of connections satisfying the conditions, extensive use of force transfer models is recommended. The general design procedure of connection detailing is to (1) to choose viable mechanism transferring forces by considering the stress level, effect of creep, shrink-age, thermal stress and allowable tolerance, (2) to predict stress level in connection elements in the connection from member design forces, (3) to confirm the stress in the connection elements not exceeding its capacity with appropriate safety margin, and (4) to confirm the additional deformation due to connection deformation not exceeding a pre-determined limitation.

INTRODUCTION

Usage of precast concrete structural elements for building construction is effective in achieving speed-up of construction nd high quality. Non-seismic precast concrete structural system have been widely used in the world. ut in most cases, they do not have enough strength and ductility. So misuse of non-seismic connections may ause catastrophic disaster if they are used for structure in high seismic zone. Hence the development of seismic onnections is essential. Extensive tests of members and subassembledges with precast concrete connection were arried out in Japan since 1980's by research institutes of construction industry. Based on those tests, the construction of moment resisting frame reinforced concrete building using precast concrete columns, beams, walls, or floor slabs have increased in 1980's and 1990's.

[1] *Dept of Architecture, School of Eng, The University of Tokyo, Tokyo, Japan. Email: shiohara@rcs.arch.t.u-tokyo.ac.jp*
[2] *School of Architecture, Faculty of Eng, Kyoto University, Kyoto, Japan. Email: nabe@archi.kyoto-u.ac.jp*

Most of those construction adopt connection details emulating cast-in-place concrete action such that they should have equivalent seismic performance as monolithic concrete members. Those connections have almost same detailing as ordinary R/C member, while minor modifications are made to eliminate difficulties in construction and achieve high productivity. The lack of explicit provisions devoted for precast concrete connections in design guidelines have been hindering local building officials to admit the usage of the precast concrete. However this construction have been well accepted by structural engineers. Unfortunately there had been no successful attempts to codify general guidelines for the structural design of moment resisting frames incorporating precast concrete.

The US-Japan cooperative research program called PRESSS on precast concrete seismic structural system had been started on 1988. It aimed to develop a precast concrete seismic structural system, which meets the different demands inherent to U.S. and Japan respectively. In the Japan-PRESSS program, a connection design manual committee chaired by Prof. Watanabe, Professor of Kyoto University was organized. The role of the committee was to develop a connection design manual for moment resisting frame. The manual was proposed in 1993 in the final reports of Japan-PRESS. This paper outlines the design concepts and introduce the state-of-the-art of the seismic design of precast concrete connection in Japan according to the manual (Japan-PRESSS Connection Design Committee 1993).

2. OUTLINE OF JAPAN PRESSS CONNECTION MANUAL

2.1 Scope

The Japan PRESSS connection manual intended to be used accompanied with a target R/C design code, e.g. existing earthquake resistant design codes applicable to ordinary cast-in-place concrete moment resisting frame structure. It did not intend to build seismic design guidelines for a new precast concrete structural system. The objective of the manual is to give engineers (1) fundamental concepts for the design of connection in precast seismic structural system and (2) practical design methods of equivalent monolithic connection.

The manual deals with connections used in moment resisting frames, the seismic design of which uses common set of equivalent static seismic forces applied to ordinary cast-in-place structures. This type of combined precast concrete structures have many advantages than thoroughly new precast concrete system, because the design is compatible with the target R/C design codes. As a result, engineers easily substitute members originally designed using a cast-in-place concrete with ones using precast concrete without serious alterations in structural design. It means construction planning and structural design using this concept becomes more adaptive.

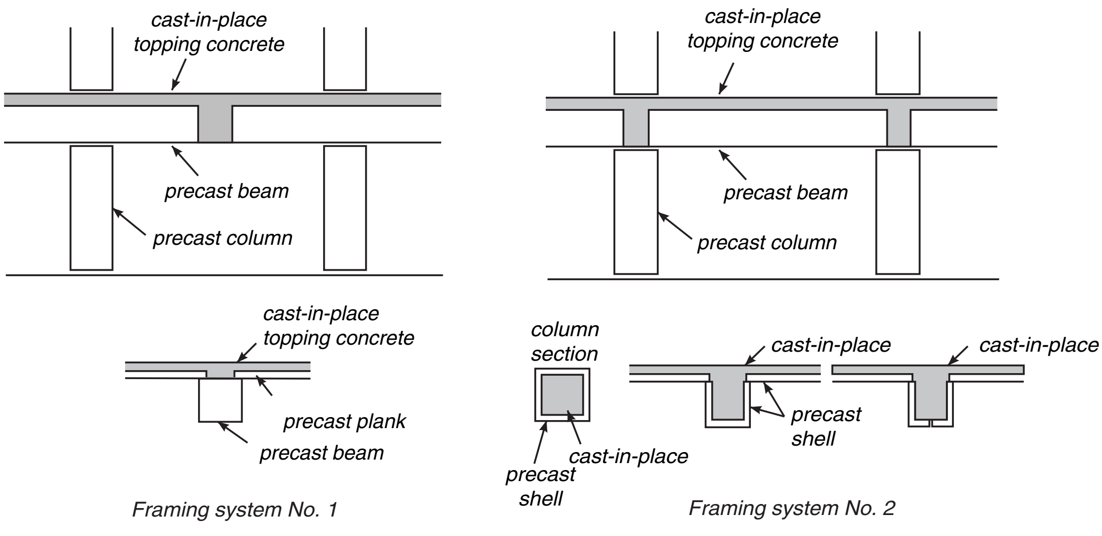


Figure 1: Typical precast concrete connection emulating cast-in-place concrete

The equivalent static seismic load in design depends on the ductility of structural system. Hence, those precast concrete connections should have equivalent strength and ductility is required, if the structure is designed using common set of seismic load. Therefore only those connection with comparable performance in terms of strength, stiffness, ductility and other properties is allowed in the manual. This connections is called an equivalent monolithic connection. The equivalent monolithic connection should satisfy all the following conditions; (1) connections which have enough stiffness such that the design stress could be predicted with necessary accuracy by structural analyses applied to monolithic cast-in-place concrete structural system, (2) connections which have equal to or larger strength such than it could transfer force occurring in member or between members such that equivalent structural seismic resistance would be maintained, (3) members with those connections should have a comparable restoring force characteristics by which no significant difference in earthquake response occur, and (4) connection should have equivalent to or superior serviceability, durability and fire resistance.

Typical connection detail which satisfy the above requirement are so-called emulating cast-in-place concrete connection. In the design of this type of connections, reinforcements such as longitudinal and transverse reinforcing steel bars need to be continuous across the concrete joint, and construction of the connection need to be completed by casting case-in-place concrete or mortar after placing precast member at the final position. To enhance the reliability of the connections, shear keys, roughening of concrete or other additional reinforcing is preferred. In the manual, connections located at plastic hinges are allowed if emulating cast-in-place concrete connections are used. Typical precast concrete systems dealt with in the manual are depicted in Fig. 1. The force-deflection relation of those members subjected to realistic stress distribution is significantly close to the behavior of monolithic one, if the connection is well detailed. Typical members dealt with are column, beam, slab, shear wall, beam-column connection. The manual does not deal with the connection utilizing prestressing.

2.2 Performance Criteria for Precast Concrete Connections

Performance demand on equivalent monolithic connections is described here in detail. They were classified under different limit states as shown in Table 1. The member incorporated with precast concrete elements and subjected to gravity load shall satisfy the following two criteria (A) demand performance for serviceability limit state subjected to gravity load and (B) demand performance for ultimate limit state subjected to gravity load. The member incorporating precast concrete elements subjected to seismic load should satisfy the following criteria in addition to the above mentioned criteria, (c) Demand performance for ultimate limit state subjected to seismic load. All the member incorporating precast concrete elements should satisfy the following criteria, (D) Demand performance for durability and fire resistance and (E) Redundancy.

To describe the equivalent performance of the member incorporated with precast concrete elements, the concept of "control cast-in-place member (CCM)" was introduced. The CCM is a virtual cast-in-place member as a reference which have common dimension, reinforcing arrangement, and same material, while they have no concrete joint or jointed reinforcement. Exception is non-framing members such as floor system. They are not required to be equivalent to CCM, because their effects on seismic response is not critical, whereas for the gravity load the floor system is required to be designed considering actual construction.

The necessity of equivalence with respect to any possible combination of load and deformation demand is not realistic. So The table 1 shows different types of demand performances including (a) strong connection and (b) ductile connection. Thus engineer could choose appropriate demand performance according to the demand strength and demand ductility to the member. For example, if a connection is located at the plastic hinge region, then demand performance for the connection for the ductile connection should be chosen.

From practical stand point of view, the performance is defined with respect to the member with precast concrete elements but the performance of connection itself. In reality, the local behavior of the connection is quite different from that of monolithic member, e.g. the local deformation such as slip or crack opening at discontinuous material could not been avoided. The meaningful definitions of equivalency in the behavior of connection itself are not feasible.

It is important that the consensus on the performance demand on equivalent monolithic connection by the engineers, because the process of verification of the equivalence of the performance become transparent. In addition to that the equivalence in performance may be verified based on rational basis by mathematical models with ensured reliability by investigation including correlation studies between tests and analyses. In other case, newly developed connection detail may be evaluated by test of member under load under simulated earthquake load of specimen. In this case, the demand performance is useful to determine target performance of the development of connection.

Table 1: Demand performance for equivalent monolithic precast concrete connections

Limit states	Loads	Members	Properties	Demand performance
(A) serviceability	$D + L$	column, girder, shear wall and beam-column join	deformation	equivalent to CCM, in terms of (a) crack width, deflection, (c) stiffness
		the other members	deformation	required performance in design in terms of (a) crack width, deflection, (c) stiffness
(B) ultimate	αD+βL	all members	stability	no collapse
(C) ultimate	D+L+E	beams and columns with no plastic hinge connection is out of hinge (Strong Connection)	yield stiffness	equivalent yield stiffness to CCM
			strength	equivalent to CCM
			ductility	no brittle or premature failure before flexural yield
		beams and columns with connection within hinge (ductile connection	elastic stiffness	within limited reduction from CCM
			yield stiffness	equivalent yield stiffness to CCM
			strength	equivalent to CCM
			ductility	no brittle or premature failure before flexural yield, and no severer strength degradation to cyclic load in comparison with CCM
			slip	limited slip deformation due to connection
		beam-column joint	strength & stiffness	equivalent to CCM
		non-seismic members	stability	no unstable collapse due to inelastic deformation of framing system
(D) diaphragms		floor system	stiffness & strength	enough stiffness and strength for the assumption of rigid diaphragms used in structural analysis
(E) durability & fire safety		all members		equivalent to CCM
D: dead load, L: live load, E: seismic load, α β: load factors				

2.3 Principles in design of precast concrete members

2.3.1 Design load

As stated in the section 2.1, the common equivalent static seismic load used for ordinary cast-in-place concrete structure may be used, whereas the effects of other loads inherent to precast structural system also needs to be taken into consideration. They include force caused by (1) change of dimension of precast element, (2) erection process, (3) volume change due to temperature, creep and drying shrinkage, etc.

2.3.2 Design of members

Figure 2 illustrates the concept of the principles of design of members incorporating precast concrete elements. Design moment and/or combination of design forces are obtained by frame analyses, in which the structures may be modeled as a cast-in-place R/C construction. Obtained moments and forces are increased to take into account the effects of necessary safety margin. Results of the analysis gives design moment, design shear, design requirement to bond. If there are limitations of story drift, eccentricity etc. specified in the codes, they are also calculated based on the same analysis. Based on the estimation of design moment, shear and their combination, geometry of the section, amount of reinforcement may be designed. The same equations for flexural strength, shear strength may be employed for the design of members.

Exceptions are allow in structural elements such as floor slab or beam supporting only gravity load. In this case, additional consideration on the support condition and construction loads should be taken into consideration. If the member has precast concrete connections, additional consideration on the connection need to be taken, by which force transfer at connection and connection elements as stated in section 2.3.3 and 2.3.4.

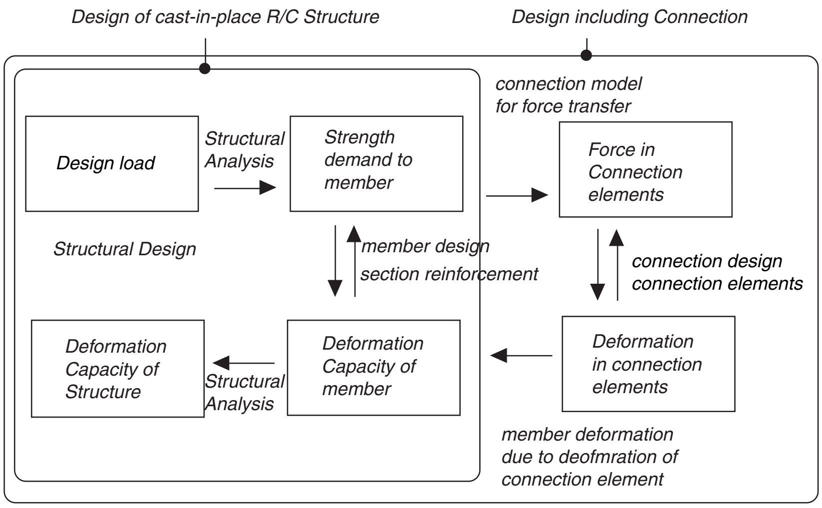


Figure 2: Design of member and connection elements

2.3.3 Member, connection and connection element

Precast concrete “member” is defined here as reinforced concrete member such as girders, beams, columns, walls beam-column connections and slabs incorporated with precast concrete elements. Hereafter, the term “connection” will be used as a joint of precast concrete to cast-in-place concrete and adjacent parts of the joint. The term “connection element” is used as elements which are components of connection. For example, boundary of discontinuous concrete interface, shear key, roughness of concrete surface, dowel and the other steel placed across concrete interface, steel bar splice, anchorage are categorized as connection elements.

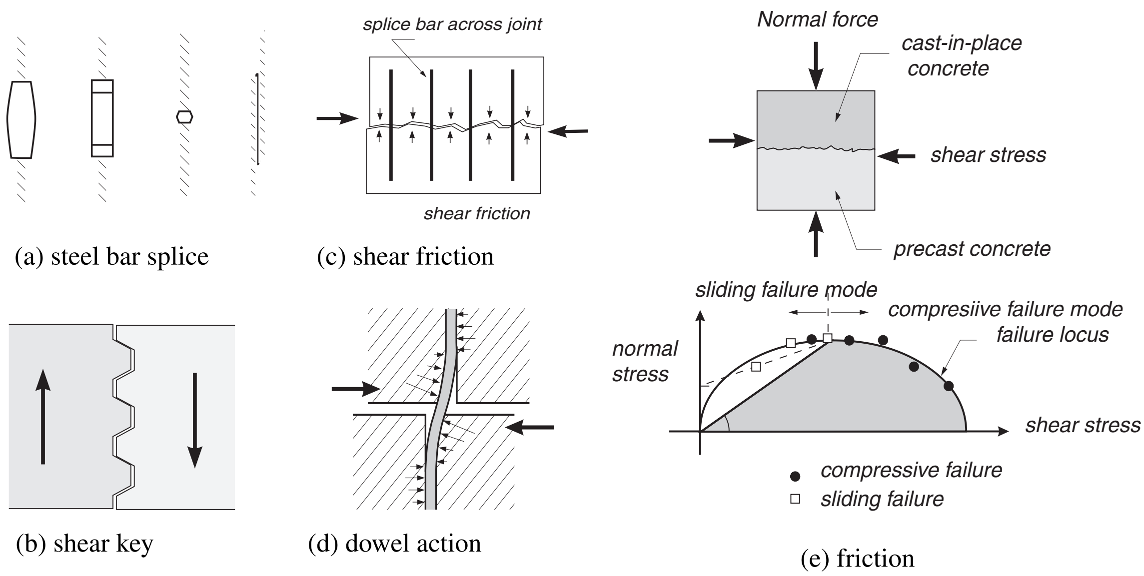


Figure 3: Various connection elements used in equivalent monolithic connections

2.3.4 Design of connection elements

The connection elements shall be designed such that they transfer the design forces occurring in it and the deformation of the connection elements shall be smaller than a tolerable limit, such that earthquake response behavior of the structural system is equivalent to the cast-in-place structural system. The design force occurred in connection elements should be calculated based on mathematical models based on the equilibrium and realistic constitutive relation of force and deformation of connection elements. Figure 3 shows the example of part of connection elements, cited in the manual. They include (a) friction, (b) shear friction, (c) splice, (d) shear keys, (e) dowel action. The information on strength, the deformation at which the strength attained are indispensable for design the connection design. In the PRESSS connection manual, equations predicting the strength of these connections based on the geometry of the connections and material properties are listed.

2.3.5 Principles in modeling of precast concrete member

Appropriate models shall be chosen to predict magnitude of the force in connection elements reflecting the realistic level of load and non-linear constitutive relation of connection elements. Other factors necessary to be taken into considerations are, (a) preciseness of precast concrete production and erection, (b) the difference of precast concrete section from cast-in-place concrete section, including the location of longitudinal bar, e.g. shift of longitudinal reinforcement to keep cover concrete thickness, allowing the splice sleeve arrangement, (c) effect of difference in compressive strength of concrete for cast-in-place concrete and precast concrete. The number of connection in a member need to be as small as possible and choosing connection elements with small deformation is necessary. The effect of additional deformation stemmed from the connection elements may be taken into account to predict the restoring force characteristic of precast concrete member, if possible. The development of kinematic models to simulate the effect of local deformation at connection elements on the total deformation of structural system may be necessary.

2.3.6 Connection Materials

The most important connection material which have significant effects on seismic safety is reinforcing bar splices. The PRESSS connection manual recommend to use mechanical splice, sleeve grout splice of welded splice, which conformed to the performance guidelines for steel bar splices, issued by Building Center of Japan in 1982. According to the guidelines, it is required to verify by tests that the tensile rupture should take place outside of splice and slip dislocation at splice should be smaller than specified limit, when it is subjected to one directional cyclic loading including tensile yielding of steel bars.

3. DESIGN OF CONNECTIONS BASED ON MODELS

3.1 General Design process

The purpose of connection design is to assure the required connection performance under given load combination. Generally, following process may be taken in the design of connection details. (1) Choice of viable connection element and stress transfer mechanism possible which can properly transfer the design moment and/or forces, where designer have to consider several conditions such as stress level, deformation behavior, creep and shrinkage, thermal stresses, tolerance and so on. (2) Prediction of stresses connection element due to design moment and/or forces.(3) Confirmation of the strength of connection elements, which should be greater or equal to the computed element stresses. (4) Confirmation of additional deflection due to slip of connection element, which should be within a allowable limit. In the PRESSS connection manual, this general process is demonstrated using design example to explain the design of different type of connections, including (a) design of member-to-member connection, (b) design of composite precast concrete member, and (c) floor slab. In this section, they are briefly introduced.

3.2 Design of member-to-member connections

Connections perpendicular to member axis are used typically at member-to-member connections including at beam ends, at center span of beams, top and bottom ends of column, or at mid height of column.

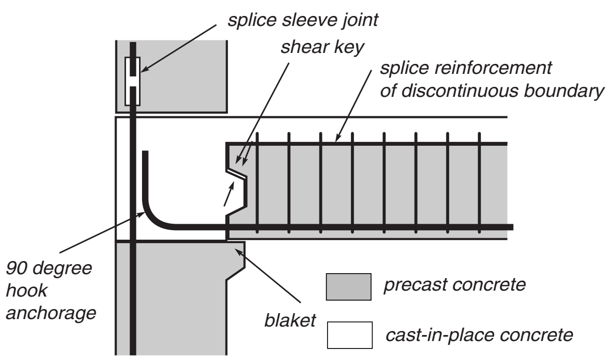


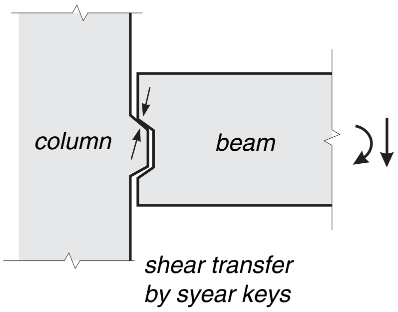
Figure 4: A typical connections at exterior beam column joints and connection elements

3.2.1 Design for flexure and axial force

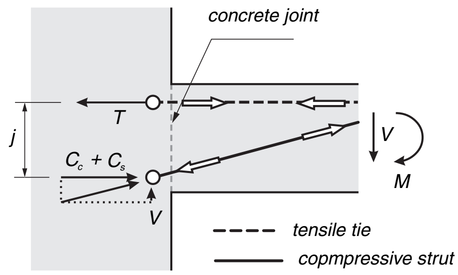
For this type of connection, (a) concrete joint and the (b) longitudinal reinforcement going across the joint may be chosen as connection elements designed for the flexure and axial force. The flexural yield strength of the connection shall exceed the design moment. The calculation of flexural strengths may be based on the flexural theory using the following assumptions; (a) plain section remains plain, (b) the compressive force due to flexure and axial action is transferred by compressive reinforcement and concrete joint, (c) tensile force due to flexure and axial action is transferred by tensile longitudinal rebar trespassing the concrete joint. For the column connections, strength and feasibility of construction of grout or mortar need to be taken into account. For connections subjected to tensile force, the degradation of tensile yield strength need to be taken into consideration. Because, dowel action due to shear force transfer may jeopardize the tensile strength of the steel. In case of dowel deformation occurs, the flexural capacity shall be reduced considering the interaction of dowel shear strength and tensile strength. The splice of longitudinal reinforcement shall have enough strength and ductility by using splice conformed to guidelines for steel bar splices, issued by Building Center of Japan, 1982. When a large and stiff splice of longitudinal reinforcement is arranged in hinge region or near hinge region, maximum moment at hinge region might exceed the predicted over strength due to strain hardening.

3.2.2 Design for shear

For this type of connection, (a) concrete joint including intended roughness and/or shear key, (b) longitudinal reinforcement bars going across the joints, (c) connection steel may be chosen as connection elements for shear. The shear strength of connection shall exceed the design shear force. The shear strength of connection need to be estimated considering (a) the magnitude of slip at which the expected shear arises should be considered when viable connection elements are chosen, (b) only one type of connection elements should to be assumed carrying the design shear except in the case where the strength different connection elements may be added based on the constitutive relation of shear resistance of the connection elements. Depending on the magnitude of shear force, different model should be used as shown in Fig. 5. For the design of serviceability limit state, the one of the following two connection elements, friction or shear key, should be used. For the design of ultimate limit state to gravity load, the design shear shall be transferred by connection elements with good ductility such as dowel action. When the connection is expected that the force is transferred by dowel action, the large slip deformation and accompanied reduction of shear strength shall be considered. In addition to that, it is necessary to add transverse reinforcement to prevent from split failure of cover concrete bearing the reaction of dowel bars. For the design of ultimate limit state to seismic load, friction at compressive concrete zone in flexure may be chosen to transfer shear force V under compressive normal stress of $C_c + C_s$.



(a) model for serviceability limit state



(b) model for ultimate limit state

Figure 5: models to estimate force in connection elements

3.2.3 Design for beam-column joint

Beam column joint may be cast-in-place or precast concrete. The allowable type of anchorage for longitudinal bars in columns or beams are (a) straight anchorage through joint, (b) hooked bar anchorage or (c) mechanical anchorage. The shear capacity of beam-column joint shall exceed the design shear of the joint. The anchorage capacity of the bars also shall exceed the design stress. The excessive deformation due to pull out of bars from beam column joint shall not significantly affect to restoring characteristics of beam-column subassemblies.

3.3 Design of composite precast member

In precast concrete beams or precast slabs, the topping concrete is popularly used. In the design of those structural element, composite effect is expected. Precast concrete shear walls are also regarded as composite members, because a shear wall is usually divided into precast elements and they are jointed at construction site, while it is designed as one unit to resist the design force. Some type of precast concrete columns use precast shell concrete, in which the precast shell is infilled with cast-in-place concrete to complete. In these type of member, the concrete joint exist along member axis as well as perpendicular to the member axis, the integrity shall be ensured. The followings are principles for design based on mathematical model.

3.3.1 Design of composite beams to shear

The connection elements shall be chosen from (a) concrete joint including intentional roughness and shear key, or (b) steel bar going across the joint. The strength of shear shall exceed the shear strength of construction joint. The design shear may be estimated based on the following consideration, (a) arbitrary critical paths for shear including concrete joint and cast-in-place concrete need to be taken consideration, (b) the effect of slip along the joint on the total force-deformation relation of structure shall be estimated and the slip shall be within some limitation, (c) the design shear shall be estimated using linear flexural theory for serviceability limit state, while the average shear considering the redistribution of shear along the joint may be considered for ultimate limit state, (d) the shear strength of connection element may be calculated based on 1) shear friction, 2) shear key, or 3) dowel action, (f) only one type of connection element for shear may be allowed to estimate shear strength, (g) for serviceability limit state, dowel action shall not be used, (h) in the joint subjected to tensile force the reduction of shear capacity shall be considered, (i) the reinforcement going across the boundary of concrete joint may count for shear resistance only if sufficient anchorages length are secured in concrete at both side of the joint.

3.3.2 The other issues

The other major issues are (a) consideration of different concrete strength of cast-in-place and precast concrete element, and (c) effect gravity load affected by type of shoring and erection sequence of precast concrete and topping concrete. The design principles for precast wall and precast columns were discussed in the PRESSS connection manual. However the detail is not presented in this paper.

4. CONCLUDING REMARKS

The precast concrete systems popularly used Japan is so-called "emulation approach" in which cast-in-place concrete is cast for completion of precast connection besides the reinforcing details are almost identical to those of an ordinary R/C buildings. In this paper, the design concepts of concrete members incorporated with precast concrete members are proposed based on the final report of Japan-PRESSS project issued in 1993. The feature of the manual is that it is based on performance approach to describe the allowable range of connections such that the scope of the manual should not limited to a particular connection detail, while it could treat similar connection detail equally as far as it is the equivalent to generic connections described in the manual. In addition to that, mechanical model to ensure force transfer were extensively introduced. Further work to codify the connection design are carried out in the task group including the author under the committee of Precast Concrete Design in Architectural Institute of Japan since 1997. The task of codification is going to be finalized in end of 2000 in fiscal year.

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