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The *fib* state-of-the-art report on the seismic design of precast concrete building structures

R. Park

Deputy Chair of fib Commission 7 : Seismic Design, Department of Civil Engineering University of Canterbury, Christchurch, New Zealand

ABSTRACT: For the last four years an international committee of Commission 7 : Seismic Design of the International Federation of Structural Concrete (*fib*) has been preparing a state-of-the-art report on the seismic design of precast concrete buildings. The report includes aspects of both precast reinforced and prestressed concrete. The committee has had contributions from 32 members, including six members from New Zealand (R. Park, D. Bull, L.McSaveney, A.O'Leary, N. Priestley and J. Restrepo). The other contributions have been from members in Canada, Chile, Indonesia, Italy, Japan, Mexico and the United States. The co-convenors of the committee are R. Park (New Zealand) and F. Watanabe (Japan). The report is due for completion in early 2003.

The main sections of the report are: state of the practice in various countries; advantages and disadvantages of incorporating precast reinforced and prestressed concrete in construction; lessons learned from previous earthquakes; precast construction concepts; design approaches; primary lateral load resisting systems (moment resisting frames and structural walls including dual systems); diaphragms of precast concrete floor units; modelling and analytical methods; gravity load resisting systems; foundations and miscellaneous.

The object of the report is to present existing practice, to recommend good practice, and to discuss current developments.

The paper presents a summary of the contents of the report.

1 INTRODUCTION

1.1 State of the Practice in Various Countries

Precast reinforced and prestressed concrete elements are widely used in the structural systems of buildings in many seismic zones of the world; for example in Asia; Europe; North, South and Central America and New Zealand. Particularly significant use of precast concrete is made in some European countries and in Japan and New Zealand for floors, moment resisting frames and structural walls.

1.2 Advantages and Disadvantages of Incorporating Precast Concrete in Construction

The main advantages of incorporating precast reinforced and precast concrete in construction are the possible increase in speed of construction, the high quality of precast concrete units and the improved durability, the reduction in site labour, and the reduction in site formwork.

The main disadvantages are that economical and effective means need to be developed for joining precast concrete elements together to resist seismic actions, the construction techniques for the joints between precast concrete elements may be unfamiliar and need to be conducted with good quality control, relatively small tolerances may need to be worked within, and enhanced craneage may be required to lift heavy precast concrete units.

2 LESSONS LEARNED FROM PREVIOUS EARTHQUAKES

Precast reinforced and prestressed concrete has had significant and successful application in earthquake resisting structures in many parts of the world. Experience of earthquakes and laboratory testing gives confidence that precast reinforced and prestressed concrete elements can be used very successfully in structures designed for earthquake resistance providing careful attention is paid to design and construction. Poorly designed and constructed precast reinforced concrete structures have performed badly in some major earthquakes due to brittle (non-ductile) behaviour of poor connection details between the precast elements, poor detailing of the elements, and poor design concepts. This has resulted in the use of precast concrete in earthquake resisting structures being regarded with suspicion in some countries. However, experience has shown that structures incorporating precast concrete elements which are well designed and constructed for seismic resistance will perform well in earthquakes.

3 PRECAST CONCRETE CONSTRUCTION CONCEPTS

3.1 Types of Connections Between Precast Concrete Elements in Moment Resisting Frames and Structural Walls

3.1.1 *Broad categories of construction*

The construction of moment resisting frames and structural walls incorporating precast concrete elements fall into two broad categories, either “equivalent monolithic” systems or “jointed” systems. The distinction between these two types of construction is based on the design of the connections between the precast concrete elements.

3.1.2 *Equivalent monolithic systems*

The connections between precast concrete elements of equivalent monolithic systems (cast-in-place emulation) can be subdivided into two categories.

a) Strong connections of limited ductility

Strong connections of limited ductility of equivalent monolithic systems are designed to be sufficient strong so that the connections remain in the elastic range when the building is satisfying the ductility demand imposed by the earthquake. That is, the yielding occurs elsewhere in the structure. Precast reinforced concrete elements have protruding longitudinal bars which are connected either by lap splices in a cast-in-place concrete joint or by non-contract lap splices involving grouted steel corrugated ducts, or by splice sleeves, or by welding, or by mechanical connectors. These connections may have limited ductility if subjected to cyclic yielding. In moment resisting frames and structural walls these connections are protected by a capacity design approach which ensures that flexural yielding occurs away from the connection region.

b) Ductile connections

Ductile connections of equivalent monolithic systems are designed for the required strength and with longitudinal reinforcing bars or grouted post-tensioned tendons in the connection region which are expected to enter the post-elastic range in a severe earthquake.

In moment resisting frames yield penetration may occur into the connection and region. The plastic hinge region may extend a distance along the end of the member as in cast-in-place construction.

3.1.3 *Jointed systems*

In jointed systems the connections are weaker than the adjacent precast concrete elements. Jointed systems do not emulate the performance of cast-on-place concrete construction. The connections between precast concrete elements of jointed systems can be subdivided into two categories.

a) Connections of limited ductility

Connections of limited ductility of jointed systems are usually dry connections formed by welding or bolting reinforced bars or plates or steel embedments and dry-packing and grouting. These connections do not behave as if part of monolithic construction and generally have limited ductility. An example of a jointed system with connections of limited ductility involving structural walls is tilt-up construction. Generally such structures are designed for limited ductility or nominally elastic behaviour.

b) Ductile connections

Ductile connections of jointed systems are generally dry connections in which unbonded post-tensioned tendons are used to connect the precast concrete elements together. The non-linear deformations of the system are concentrated at the interfaces of the precast concrete elements where a crack opens and closes. The unbonded post-tensioned tendons remain in the elastic range. These connections have the advantage of reduced damage and of being self-centering (ie, practically no residual deformation) after an earthquake.

Hybrid systems have dry connections which combine both unbonded post-tensioned tendons and longitudinal steel reinforcing bars (tension/compression yield) or other energy dissipating devices (eg, flexing steel plates or friction devices). The post-elastic deformations of the system during an earthquake are again concentrated at the interfaces of the precast concrete elements where a crack opens and closes.

3.2 **Tolerances and Erection**

The design and construction of precast concrete structures to resist seismic actions requires an appreciation of product, erection and interfacing tolerances. The designer and erector must possess knowledge of the capabilities and limitations of precast element production processes, and an understanding of how the structure will be safely assembled.

4 DESIGN APPROACHES

The required performance criteria for structures incorporating precast reinforced concrete elements adopted in seismic design are generally similar to those for cast-in-place construction. Currently for seismic design at the ultimate limit state force-based design is used along with the capacity design approach (see for example Standards New Zealand, 1995 and Park, 2002).

Lateral load resisting systems can be designed for nominally elastic, limited ductility or ductile response. The magnitude of the design lateral forces decreases, whilst the complexity in the detailing of the reinforcement in the critical regions increases, as the design approach goes from nominally elastic to a fully ductile response. For structures, incorporating precast concrete elements emulating ductile cast-in-place construction the detailing rules are as for monolithic structures. The post-elastic mechanism of deformation should involve flexural yielding at plastic hinges. A capacity design procedure should be used to ensure that the mechanism can be maintained during the design earthquake.

5 PRIMARY LATERAL FORCE RESISTING SYSTEMS

5.1 Introduction

In general, lateral force resisting systems built incorporating precast concrete elements are either "equivalent monolithic" or "jointed" moment resisting frames or structural walls. Dual systems, in which moment resisting frames and structural walls are combined to provide lateral force resistance in the same direction, are also used, but to a much lesser extent. However it is common practice, particularly in regions of low and moderate seismicity, to combine moment resisting frames or structural walls with frames carrying mainly gravity loading.

5.2 Moment Resisting Frames

5.2.1 *Ductile equivalent monolithic reinforced concrete frames incorporating precast concrete elements*

a) Arrangement of members

Four equivalent monolithic ductile reinforced concrete construction systems used in Japan (Architectural Institute of Japan, 2000) and New Zealand (Centre for Advanced Engineering, 1999) designed for weak beam-strong column behaviour are shown in Figure 1.

In **System 1** the precast concrete beam elements are placed between either precast or cast-in-place concrete columns, seated on the cover concrete below and/or propped adjacent to the columns. Reinforcement is then placed in the top of the beams and in the beam-column joint cores. One approach with this system, typically used in New Zealand, is to splice the beam bottom bars using hooked anchorages in the joint core (see (a) of System 1). An alternative approach, typically used in Japan, is for the bottom bars to be continuous through the joint (see (b) of System 1). The faces of the precast beam elements are either keyed or roughened.

In **System 2** the vertical column bars of the column below the joint protude up through vertical corrugated steel ducts in the beam unit where they are grouted and pass into the column above. The beams are connected using a cast-in-place concrete joint at midspan (see Figure 1).

In **System 3**, T-shaped or cruciform shaped precast concrete elements are connected vertically by column bars and horizontally by a cast-in-place concrete joint at midspan (see Figure 1).

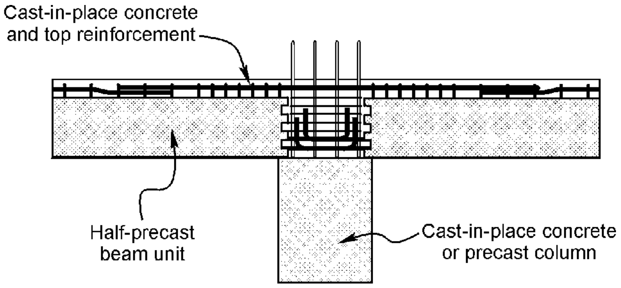
In **System 4**, mainly used in New Zealand, pretensioned prestressed concrete U-beams and cast-in-place reinforced concrete are used (see Figure 1).

In all systems a precast concrete floor system is placed seated on the top of the precast concrete beam elements and spanning between them.

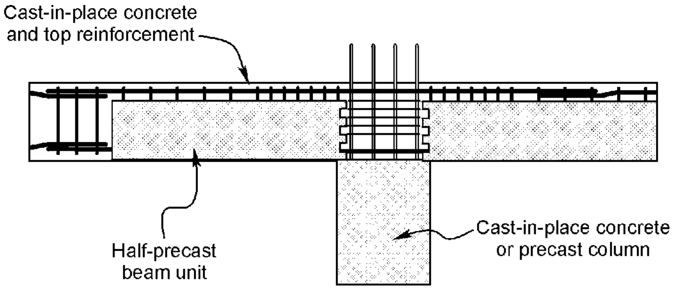
b) Column-to-column and beam-to-beam connections

The precast reinforced concrete column elements in Systems 2 and 3 can be spliced either at the end above the beam or at mid-height. Either grouted steel sleeves (see Figure 2(a)) or non-contact lap splices involving grouted corrugated steel ducts can be used (see Figure 2(b)). In Figure 2(b) the longitudinal bars protruding from the precast column bars "G" are grouted into corrugated metal ducts in the mating column. Adjacent to the ducts there are two smaller diameter bars, bars "L", of about the same cross sectional area as the grouted bar. Those bars are lap spliced a distance not less than the development length of the small diameter bars. The gap between the jointed surfaces is grouted at the same time as the ducts. Note that splices at the end of columns can be protected by a capacity design approach to prevent plastic hinging occurring in the column there.

The precast reinforced concrete beam elements in Systems 2 and 3 are connected by a cast-in-place concrete joint near midspan (see Figure 1). In New Zealand bar laps are favoured. Straight bar laps are used if the cast-in-place joint is long enough (see Figure 3(a) and (b)).

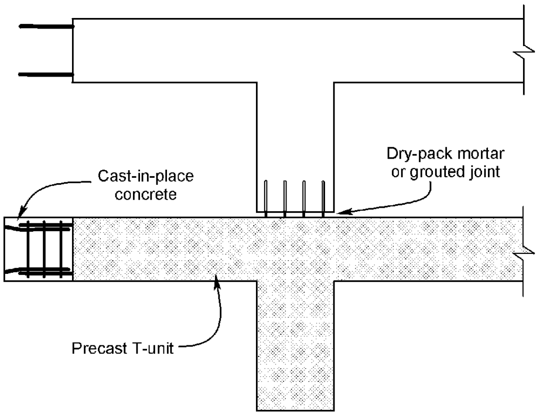


(a) Approach using hooked bottom bar anchorage

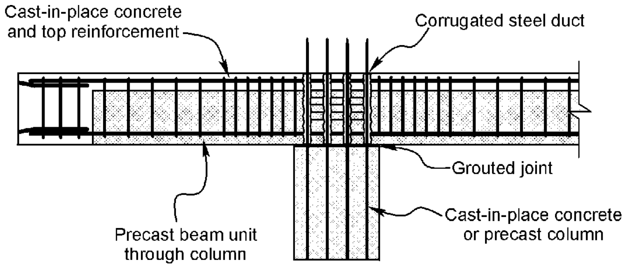


(b) Approach using straight bottom bars

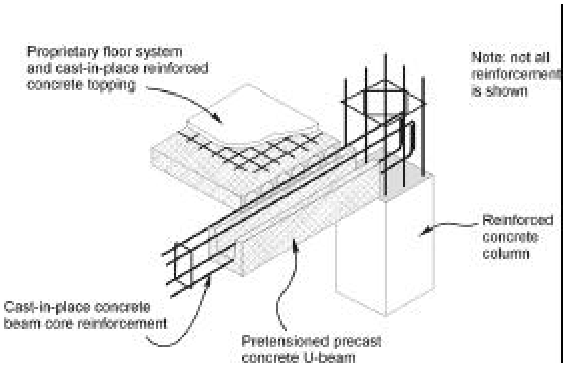
System 1



System 3



System 2



System 4

Figure 1. Ductile equivalent monolithic reinforced concrete Systems 1, 2, 3 and 4

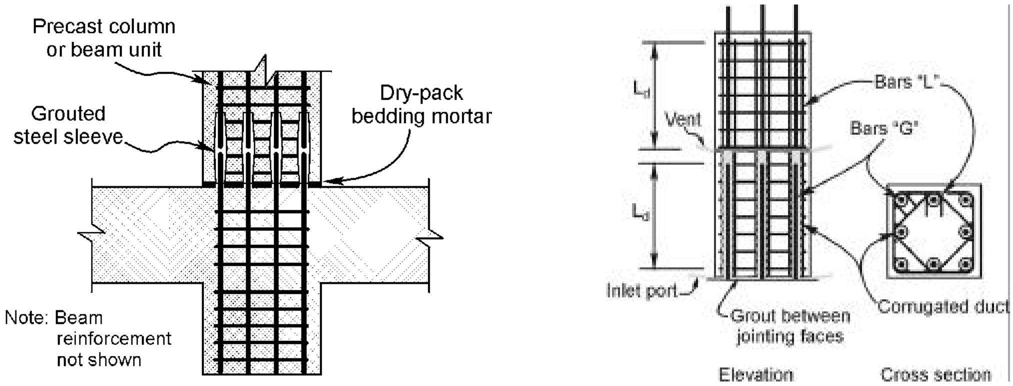
Alternatively for shorter cast-in-place joints hooked bar laps can be used or double hooked drop-in-bars (see Figure 3(c)). The details shown in Figure 3(b) and (c) are easier to assemble during erection. In Japan welding the bars or mechanical couplers, or grouted steel sleeves (see Figure 3(d) and (e)) are favoured.

c) Experimental verification

All of the equivalent monolithic reinforced concrete systems 1, 2, 3 and 4 and beam-to-beam and column-to-column connections have had experimental verification by simulated seismic load testing in Japan or New Zealand. Generally, if well designed and constructed they have been found to behave as if of cast-in-place construction.

5.2.2 *Jointed reinforced concrete moment resisting frames of limited ductility incorporating precast concrete elements*

Some jointed reinforced concrete frame systems that have relatively weak connections between precast elements, achieved mainly by welding or bolting and dry packing, have been attempted. Such systems should be used with caution since they can have very limited ductility.



(a) Grouted steel sleeves (b) Non-contact lap bar splices

Figure 2. Column-to-column reinforced concrete connections

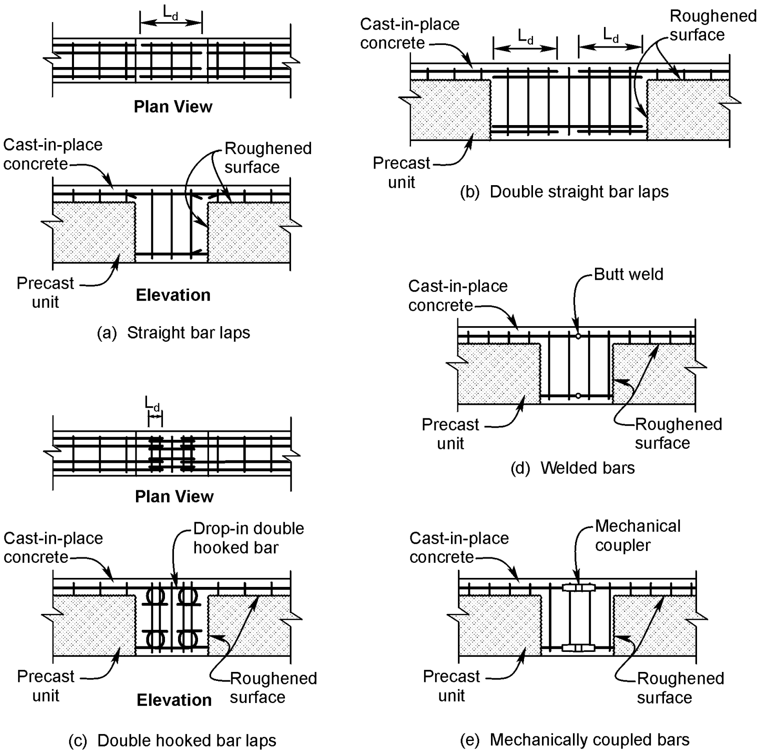


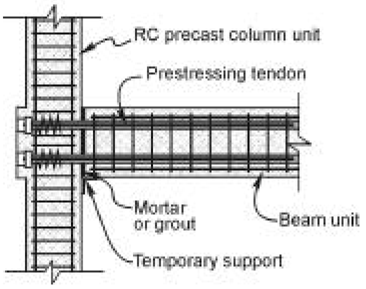
Figure 3. Beam-to-beam reinforced concrete connections

5.2.3 *Ductile equivalent monolithic moment resisting frames incorporating bonded post-tensioned or pretensionsed tendons*

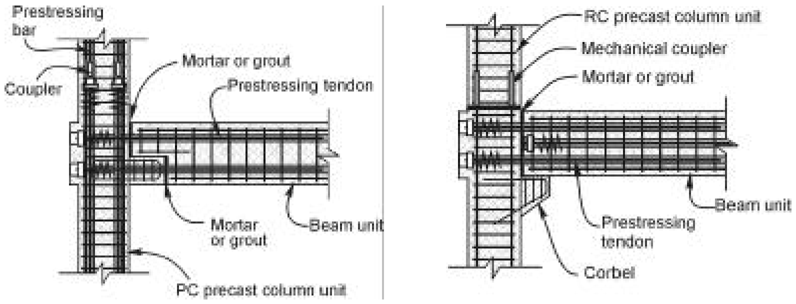
a) Arrangements with bonded post-tensioned beams

Ductile equivalent monolithic construction incorporating grouted post-tensioned tendons is widely used in Japan and has been used in New Zealand since the 1960s. This type of construction has had experimental verification and has behaved well in earthquakes.

The two main systems used are shown in Figure 4. Both involve precast concrete beam units placed between precast concrete columns. In System 1 the precast concrete beams have a temporary seating on steel brackets or are propped. Mortar or grout is placed in the gap at the beam ends. The post-tensioning operation is performed and completed by grouting the tendons. In System 2 the precast concrete beams are seated on concrete corbels. The ends of the beams can be dapped or prismatic.



System 1



System 2

Figure 4. Equivalent monolithic post-tensionsed systems 1 and 2 with grouted post-tensioned tendons

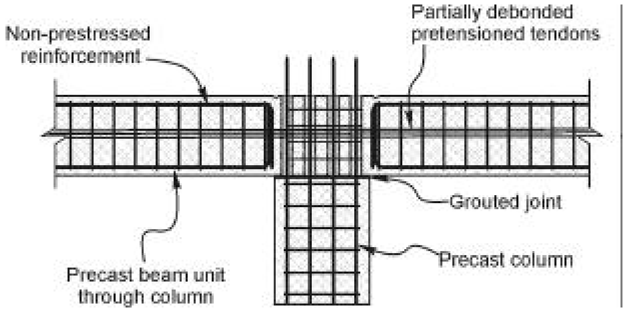


Figure 5. Equivalent monolithic system with pretensioned beam units through the columns

In New Zealand it is recommended for System 1 that the post-tensioned tendons in the beam be anchored in an end block outside the column so as to move the bursting stresses from the anchorage away from the beam-column joint which may already be severely stressed as a result of diagonal tension.

b) Arrangement with pretensioned beams

The system shown in Figure 5 consists of multi span pretensioned beams with specified lengths of the pretensioned tendons debonded. The beam-to-column connection in this system is identical to that of System 2 of Figure 1.

5.2.4 *Ductile jointed moment resisting frames incorporating unbonded post-tensioned tendons and non-prestressed reinforcement*

In ductile jointed systems the precast concrete elements are connected by unbonded post-tensioned tendons.

Hybrid systems are jointed systems which combine unbonded post-tensioned tendons with longitudinal non-prestressed reinforcing bars (tension/compression yield). Hybrid systems were developed in the United States and adopted in the PRESSS (Precast Seismic Structural Systems) programme (Priestley et al, 1999). Figure 6 shows an example. The precast beams are connected to multi-storey columns by unbonded post-tensioned tendons that run through a PVC duct at the centre of the beam. The gap between the beam and the column is filled with fibre reinforced grout. The tendon prestress is such as to ensure it will not reach the limit of proportionality during an earthquake. Non-prestressed steel reinforcing bars are placed in corrugated ducts on the top and bottom of the beam and through the columns and grouted. These bars provide energy dissipation by yielding in tension and compression over debonded regions next to the beam-to-column connection. The non-linear deformations come from the opening and closing of the crack at the interface between the precast concrete elements. The system has the advantage of reduced damage during an earthquake and of being self centering (ie, practically no residual deflection after an earthquake).

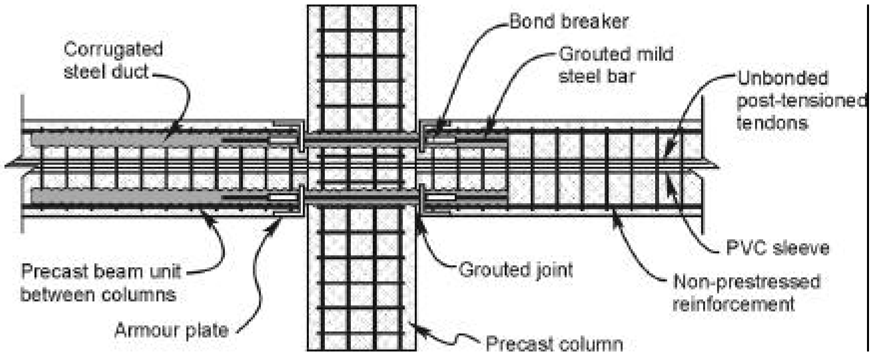


Figure 6. General reinforcing details of a hybrid frame system

5.3 **Structural Walls**

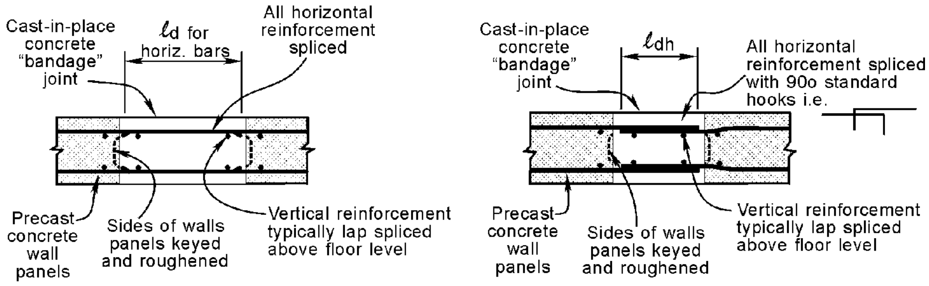
5.3.1 *Equivalent monolithic reinforced concrete structural walls incorporating precast concrete elements*

New Zealand practice for horizontal and vertical joints in monolithic structural wall construction is discussed below.

At the horizontal joints between precast reinforced concrete wall panels or foundation beams the ends the panels are usually roughened to avoid sliding shear failure and the joint made using mortar or grout. The vertical reinforcement protruding from one end of the panel and crossing the joint is connected to the adjacent panel or foundation beams by means of either grouted steel splice sleeves or grouted corrugated metal ducts much as for the column-to-column connections in Figure 2.

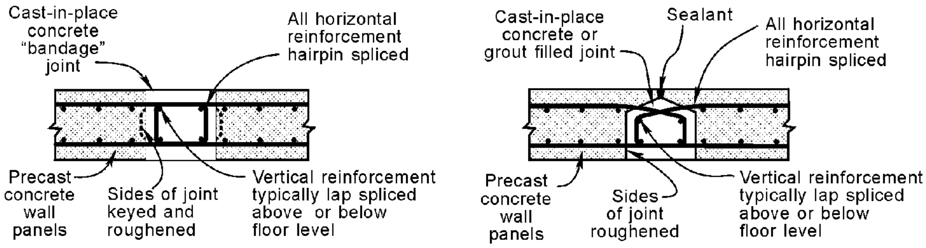
Vertical joints between precast concrete wall panels are typically strips of cast-in-place concrete into which horizontal reinforcement from the ends of the adjacent panels protrude and are lapped. Figure 7 shows some possible vertical joint details between precast wall panels that make use of cast-in-place concrete. The widths of the strips of cast-in-place concrete are determined by code requirements for lap lengths of horizontal reinforcement. Figure 7(a) shows a joint with sufficient width to accommodate the lap splice length of the straight horizontal bars that protrude from the precast wall panels. Figure 7(b) shows hooked lap splices that enable the width of joint to be reduced. Figure 7(c) and (d) show hairpin splice bars which may not be convenient to construct since once the lapping bars have been overlapped the ability to lower the precast panels over starter bars is very restricted.

Support for precast floor units at walls can be achieved in a number of ways. Figure 8 shows two examples for exterior walls. In Figure 8(a) the precast wall panel is continuous through the connection and the floor is seated on a steel angle anchored to the precast wall panel. Alternatively a concrete corbel could be used. In Figure 8(b) the precast wall panel is segmented and the floor is seated on a recess in the wall.



(a) Straight Lap Splices

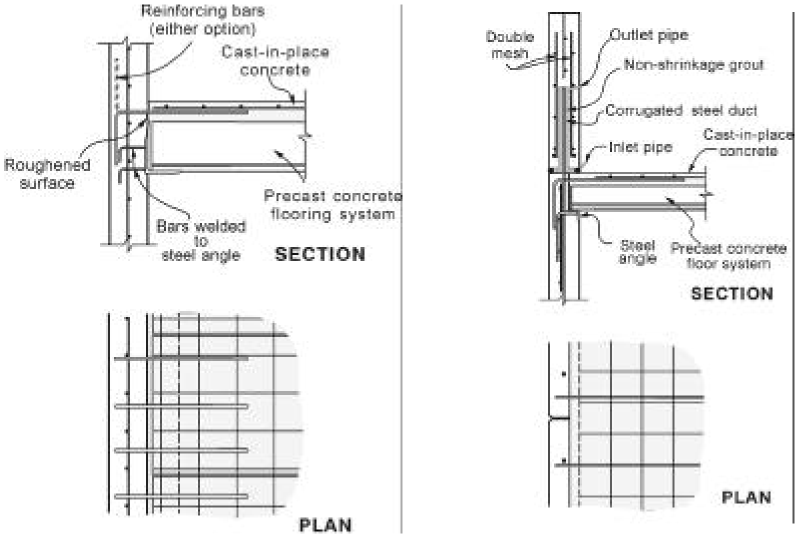
(b) Hooked Lap Splices



(c) Hairpin Lap Splices

(d) Hairpin Lap Splices

Figure 7. Examples of vertical joints for equivalent monolithic precast reinforced concrete structural wall construction



(a) Continuous wall unit with cast-in-steel bracket

(b) Segmented wall with recess and grouted horizontal joint

Figure 8. Examples of precast reinforced concrete exterior wall-to-precast slab floor connections

5.3.2 *Jointed reinforced concrete structural walls of limited ductility incorporating precast concrete elements*

In jointed wall construction of limited ductility the connection between the precast reinforced concrete wall panels is such that planes of significantly reduced stiffness and strength exist at the interface between adjacent precast concrete wall panels. Such construction has been extensively used in New Zealand in tilt-up construction generally of one to three storey apartment, office and industrial buildings. Generally tilt-up wall panels are secured to the adjacent elements using jointed connections comprising various combinations of concrete inserts, bolted or welded steel plates or angle brackets, and lapped reinforcement splices within cast-in-place joining strips. Tilt-up construction is generally designed for elastic or limited ductile response.

5.3.3 *Ductile hybrid structural walls*

Hybrid structural walls are jointed walls which contain unbonded post-tensioned tendons with longitudinal steel reinforcement and/or other energy dissipating devices. They were developed in the United States and adopted in the PRESSS Programme (Priestley et al, 1999). Figure 9 shows a wall system adopted. The post-elastic demand is concentrated at the joints.

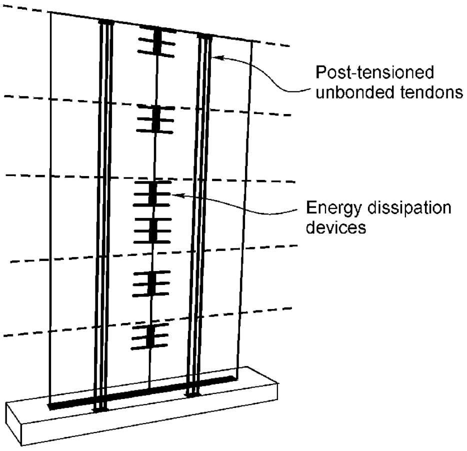


Figure 9. A hybrid structural wall system developed in the PRESSS Programme (Priestley et al. 1999)

6 DIAPHRAGMS

6.1 **Introduction**

As well as carrying gravity loading, floors and roofs need to transfer the in-place imposed wind and seismic forces to the supporting structures through diaphragm action. A convenient way to achieve diaphragm action when precast concrete floor and roof elements are used is to provide a cast-in-place reinforced concrete topping slab over the precast units. Where precast concrete floor and roof units are used without an effective cast-in-place concrete topping slab, in-plane force transfer due to diaphragm action must rely on appropriately reinforced joints between the precast units.

6.2 **Support Details**

Adequate support of precast concrete floor and roof units is one of the most basic requirements for a safe structure. The units should not lose their support.

One source of movements during severe earthquakes, which could cause precast concrete floor and roof units to become dislodged, is that beams of ductile moment resisting frames tend to elongate when forming plastic hinges, which could cause the distances spanned by precast concrete floor and roof members to increase. This elongation may be in the order of 2-4% of the beam depth per plastic hinge (Centre for Advanced Engineering, 1999) as has been observed in tests where expansion was free to occur. This elongation occurs because of tensile yielding of longitudinal reinforcement due to plastic strains. It may cause tearing away of diaphragms in extreme events.

Two types of support for precast concrete hollowcore or solid slab flooring units seated on precast concrete beams, identified by the New Zealand guidelines (Centre for Advanced Engineering, 1999) are shown in Figure 10. The differences between these types are the depth of the supporting beam prior to the cast-in-place concrete being placed. Figure 10 also shows special support reinforcement intended to carry the vertical load in the event of the precast floor units losing their seating. For precast hollowcore units it can either be placed in some of the cores which have been broken out at the top and filled with cast-in-place concrete or it can be grouted into gaps between the precast units. Plain round well anchored reinforcement is used. Bond failure propagating along the plain round bars results in extensive yielding along the bars therefore allowing substantial plastic elongation before fracture.

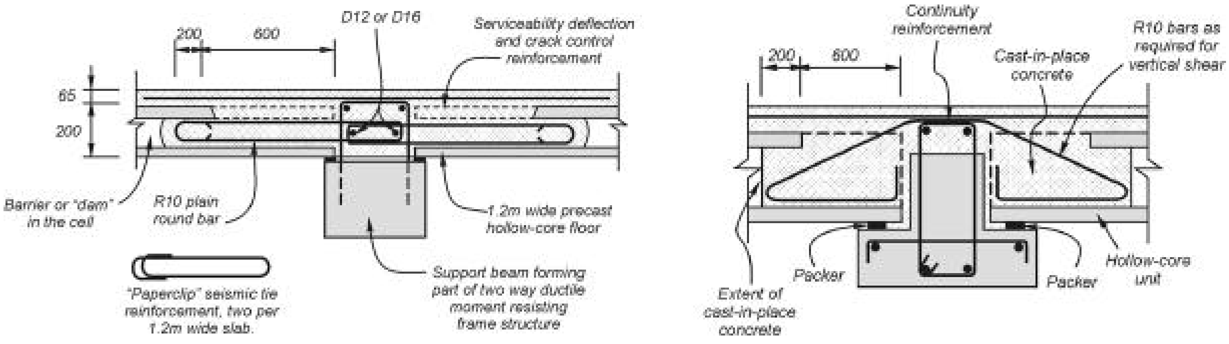


Figure 10. Examples of support and special support reinforcement at ends of precast concrete hollowcore floors (Centre for Advanced Engineering, 1999)

6.3 **Detailing for Other Type of Localised Displacements**

Other sources of localised displacements in diaphragms, as well as elongation at plastic hinges in reinforced concrete beams, are strut and tie node points where diaphragm forces pass around floor openings or irregularities in floor plan, transfer diaphragms, sliding joints in vertically jointed walls, and pinned-end beams.

Two procedures that can be used to accommodate these displacements are:

(1) Isolate the precast components from any high displacement demands, with sliding supports and/or compressible joints. This method is preferred for relatively brittle extruded or slip-formed hollowcore sections, and for some of the more brittle beam and block flooring systems.

(2) Reinforce the precast units, and any composite topping concrete to provide adequate ductility to resist the required gravity loads during, and after, the imposed displacement (for example as in Figure 10).

7 MODELLING AND ANALYTICAL METHODS

7.1 **Modelling**

7.1.1 *Introduction*

Significant differences in behaviour of precast concrete systems at both local and global level can be expected depending on the longitudinal steel in the connection (post-tensioned tendons on ordinary reinforcement or some combination), on the characteristics of the bond conditions (from fully bonded to fully unbonded) as well as on the other structural details such as the anchorage solutions (lap splices, end hooks, grouted steel ducts or sleeves, mechanical).

7.1.2 *Fibre element model*

A model based on fibre elements should be able to directly incorporate global relationships (equilibrium and compatibility) involving single members or the whole system, and thus accurately predict the behaviour of either bonded or unbonded connections/systems. The reliability of fibre element models in modelling the behaviour of monolithic reinforced concrete members under cyclic loading, including bar-slip phenomena due to bond deterioration has been extensively demonstrated and recognised in the literature. Recently jointed unbonded post-tensioned frames and walls have been modelled successfully.

7.1.3 *Lumped plasticity model*

A lumped plasticity model relies on the assumption that the main inelastic demand is accommodated within discrete critical sections (ie, beam-column, column-foundation or wall-foundation interfaces). While in monolithic connections (precast/reinforced or prestressed, emulating the cast-in-place concrete solutions), flexural cracking is expected to develop in the structural elements, the peculiar mechanics of precast jointed and hybrid systems guarantee a concentration of the inelastic demand at the interface while the structural members remain essentially elastic and suffer limited damage. In the latter case, thus, the seismic response of jointed and hybrid precast/prestressed frame or wall systems can be accurately predicted using one-dimensional beam elements, representing the members, with concentrated inelastic behaviour at the critical sections (ie, beam-to-column or column-to-foundation interfaces). The moment-rotation cyclic behaviour of the critical section of a hybrid connection system can be obtained by combining the hysteretic response of prestressed system with that of the energy dissipating system. For example, Figure 11 shows the idealised flag-shape hysteretic rule for a hybrid system.

7.2 **Analytical Methods**

Analytical methods that can be used are similar to those for cast-in-place construction. Depending on the circumstances they can be either elastic or inelastic and either static or dynamic.

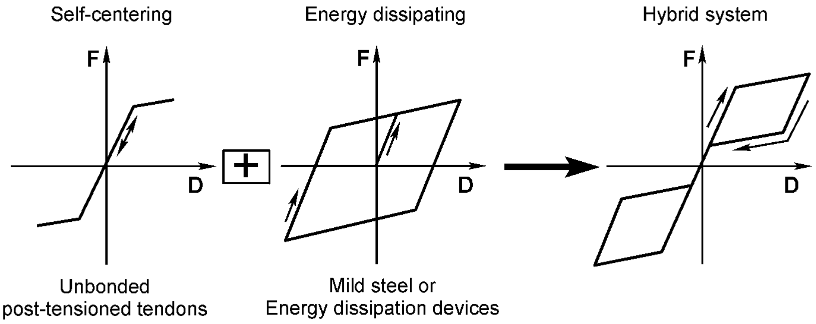


Figure 11.
Idealised flag-shape hysteretic rule for a hybrid system

8 GRAVITY LOAD RESISTING SYSTEMS

Gravity load resisting elements and systems are designed to carry mainly gravity loads. Although they are subjected to sway caused by earthquakes they do not provide significant horizontal load resistance. The elements need to be designed and detailed so that they retain their gravity load carrying capacity during and after major seismic induced lateral deformation of the main horizontal load resisting structure by either:

- Remaining in the elastic range when deflected laterally
- Deforming in a ductile manner when deflected laterally into the post-elastic range
- Being separated from the structure so that they do not deflect into the post-elastic range

9 FOUNDATIONS

The foundations for precast concrete building structures are generally similar to those for cast-in-place concrete construction.

One difference is that the simplest way to connect precast concrete columns to foundation beams is to use a socket-base connection. In such a foundation the end of the column is inserted in a vertical recess formed in the reinforced concrete foundation beam and grouted in place. Socket-base connections are normally used only for low rise buildings since high axial tensions in the column due to overturning moment are difficult to provide for. An embedment depth of the column of at least 1.5

times the column section depth is needed to achieve behaviour as for a monolithically constructed connection unless adequate shear keys are provided on the column and socket surfaces.

A significant use of precast concrete for foundations is for piles, either of reinforced concrete or of pretensioned prestressed concrete. Prestressed precast concrete piles are often preferred because of the high durability of high strength concrete, easiness of handling, suitability for longer lengths, ability to take hard driving, and high load carrying capacity. Piles in soft and variable soil strata need to be designed to be able to undergo significant lateral displacements. Particularly vulnerable are the regions near the pile cap and the pile tip. The ductility of prestressed concrete piles can be considerably enhanced by the use of high yield strength lateral confining reinforcement and by the use of prestressing steel with high elongation at fracture.

10 OTHER APPLICATIONS IN BUILDINGS

Precast concrete elements have been widely used for the construction of shell and folded plate roofs and for various non-structural elements such as stairs, cladding panels and partitions. Non-structural elements need to be constructed in a manner that permits unrestricted movement of the seismic resisting structure during an earthquake.

11 CONCLUSIONS

Precast reinforced concrete can be used successfully in structures designed for earthquake resistance, providing careful attention is given to conceptual and detailed design and to fabrication and erection. The *fib* state-of-the-art report on the seismic design of precast concrete building structures is intended to assist designers and constructors to provide safe and economical applications of structural precast concrete and at the same time to allow innovation in design and construction to continue.

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