Conceptual development: Low loss precast concrete frame building system with steel connections

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ABSTRACT: Monolithic reinforced concrete (RC) frames and conventional pre-cast concrete structural systems are prone to develop severe damage under high seismic excitations, which makes buildings using these systems less sustainable because of the downtime and repair cost required to fully restore the functionality of the damaged building. For this reason, researchers are exploring alternate RC building systems that minimize the downtime and seismic losses.

In this paper, schematic development of a sustainable demountable precast RC frame system, in which the precast members are connected with steel angles/plates, steel tubes/plates and high strength friction grip (HSFG) bolts, is discussed. The concept of this system allows a mechanical pin to be used in the gravity frame connections such that only the seismic frames share the lateral force imposed by earthquakes and the gravity frames do not damage at all in earthquakes. In the proposed precast structural system, damaged structural elements in seismic frames can be easily replaced with new ones; thereby rendering it a definitely repairable and low loss system, despite not being a damage avoidance solution. The load transfer mechanism from the weak beam to the strong column through the connection is explained and a model is proposed to analyse the connections. Pros and cons of the proposed precast framing system and its application in practice are also discussed in the paper.

1 INTRODUCTION

In the modern world, concrete has dominated the construction sector because of its availability and material properties. Concrete structures are constructed in two ways: cast-in-situ and precast. Precast concrete structures can be defined as structures where the majority of structural components are standardized and produced in concrete yards away from the site and then transported to the site for assembly. Precast concrete construction is being adopted in many countries for its potential advantages. The performance of precast structural system in resisting lateral loads depends on the behaviour of connections. The implementation of innovative ideas for connecting precast elements together, and subsequent verification through experimental procedures, has resulted in significant advances for the precast concrete industry in seismic regions of the world in the past two decades. For example, in New Zealand precast concrete has been used in moment resisting frames since the 1980s (Park 1990).

Structural behaviour of precast structures differs from monolithic cast-in-situ concrete structures. From a general point of view, there are two alternatives to design precast structures. One choice is the use of precast concrete elements interconnected predominantly by hinged connections, whereas the other alternative is the emulation of monolithic RC construction. The emulation of the behaviour of monolithic RC constructions can be obtained using either ‘‘wet’’ or ‘‘strong’’ (dry or partially dry) connections. A ‘‘wet’’ connection between precast members uses cast-in-place concrete or grout to fill the splicing closure. Precast structural systems with wet connections must then comply with all requirements applicable to monolithic RC constructions. A ‘‘strong’’ connection is a connection, not necessarily realized using cast-in situ concrete, that remains elastic while designated portions of structural members undergo inelastic deformations under the design actions (Bournas et al 2013). Generally “strong” dry connections are achieved with use of dowels or anchor rods, steel billets, steel plates, and steel angles. Many researchers have proposed dry connections with different configurations and experimentally validated and found that these systems can be considered as semi-rigid connections which primarily depend on dowel action for force transfer from beam to column (Elliott et al 2003a, Mohamed 1992 & Negro et al 2012). To the author's knowledge, there is limited research in the development of demountable precast system with strong rigid dry connection.

The present research is focused on development of sustainable demountable precast RC frame building system using "strong" dry connection consisting of steel angle or steel tube, stiffened steel plates and pre-tensioned high strength frictions grip (HSFG) bolts. The main advantages of the proposed sustainable precast frame building system are:

1. *Quick to construct: Building system without use of cast-in-situ concrete, site formwork, and can be erected in quick time.*

   The proposed system doesn't need any cast-in-situ concrete; the connections between floor-floor, floor-beam, beam-column and column-foundation are made using steel elements (i.e. stiffened steel angle or steel tube) and pre-tensioned high strength bolts. This system can be erected in quick time which leads to significant reduction in overhead project cost and increased financial return due to earlier occupancy of the building.

2. *Simple system: Building system is simple to analyse, design and construct.*

   No specialist knowledge is required in the analysis, design and construction of the proposed precast frame building system. As the precise elements and connections to be used in the system are simple and have been used in industry for several years, general builders can easily erect the proposed system without much difficulty. In addition, the system does not require very precise construction and fabrication tolerance.

3. *Demountable: Building system can be demounted at any time during the life span of building.*

   The connections between the precast elements of the frame building are made such that the building can be easily demounted when/if needed without damaging the components. The proposed system enables financial savings through dismantle and reuse (rather than demolish).

4. *Easily upgradable: Building system can be easily upgraded or strengthened.*

   The proposed building system can be upgraded if higher strength is required due to change of building occupancy or change in design code/demand. Higher strength can be achieved by replacing the weakest frame elements with bigger/stronger ones or by adding diagonal bracing elements with little intervention (as the steel connection can be predesigned to accommodate the bracing elements when/if needed in future).

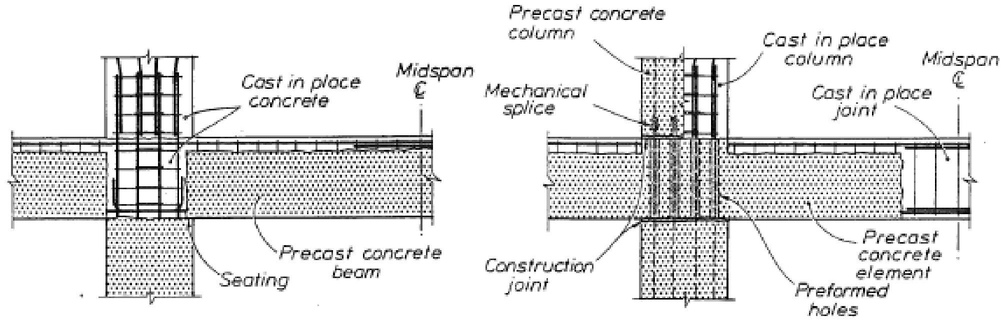
5. *Easy/fast to repair/Insurance compliant: System with easily replaceable damaged elements, thereby making it an earthquake resilient building system and compliant to insurance policy "like for like as when new".*

   The damaged structural beams and columns in earthquakes can be easily replaced with new one within short time (which leads to significantly less downtime loss); thereby rendering it a definitely repairable and low loss system, despite not being a damage avoidance solution. The damaged building can be recovered exactly to the original state (or stronger, if needed) in a short time which leaves no room for ambiguity in terms of compliance to the common insurance policy of "like for like as when new".

This paper describes the conceptual development (including schematic layout) of the proposed demountable precast frame building system, and available lateral load resisting options within the proposed system. It also explores an analytical model for estimating the connection capacity.

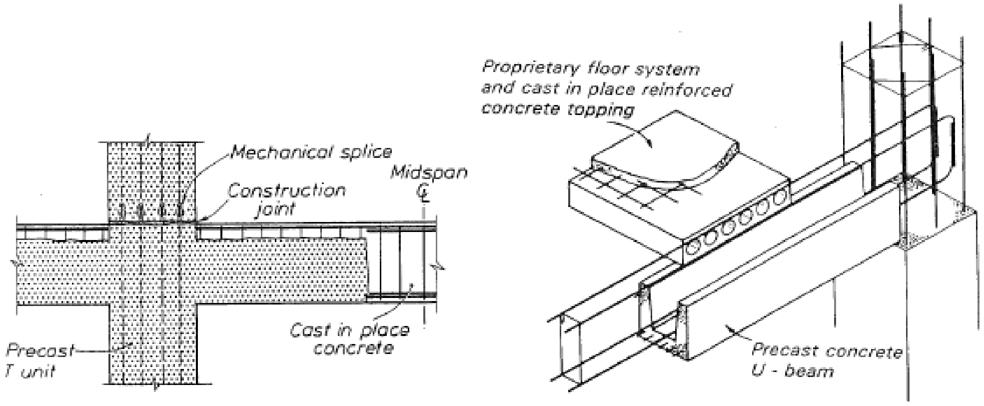
2 PRECAST BUILDINGS AND THEIR PERFORMANCE IN CANTERBURY EARTHQUAKES

In New Zealand, precast reinforced concrete moment resisting frames are very common since 1980's. In precast building systems, joints between precast elements are normally designed to emulate monolithic construction so that the whole structure shows equivalent monolithic behaviour during an earthquake. There are four ways of achieving equivalent monolithic behaviour in conventional precast frames, which are shown in detail in Figure 1.



(a) System 1 - Precast Beam Units between Columns

(b) System 2 - Precast Beam Units through Columns



(c) System 3 - Precast T or Cruciform Units

(d) Precast Concrete System Involving Shell Beams

Figure 1. Commonly used arrangements of Precast Members and Cast in Place Concrete for Constructing Moment Resisting Reinforced Concrete Frames in New Zealand. (Restrepo 1992)

In system-1, the precast beam elements are placed between columns and seated on the cover concrete of the previously cast-in-place or precast column below and/or propped adjacent to the columns. A precast concrete floor system is placed, seated on the top of the precast beam elements and spanning between them. Reinforcement is then placed on the top of the beams, over the precast floor and in the beam column joint cores. The topping slab over the floor system and the beam-column joint cores is cast-in-situ (Fib-27 2003). In system-2, the precast beams are seated on steel shims creating a construction joint 10 to 25mm thick. Protruding column longitudinal bars pass through precast preformed vertical holes in the beams and protrude above the beams top surface. The holes in the precast beam elements are formed by corrugated steel ducting. The vertical ducts and the horizontal construction joint at the bottom of the precast beams are grouted in one operation. A precast concrete column is then positioned above the precast beam using grouted vertical laps or grouted steel sleeves to connect the vertical column bars (Restrepo 1992).

In system-3, T–shaped, cruciform precast concrete elements or even multi-storey cruciform units are used. In this arrangement the vertical column bars in the precast units are connected using grouted steel sleeves. Cast-in-place connections of the beams for this system are identical to those employed for System 2 (Fib-27 2003).In system-4, pre-tensioned precast concrete beam shell units are used as permanent formwork for beams. The precast U-beams support the self-weight and construction loads and act compositely with the reinforced concrete core when subjected to other loading in the completed structure. Precast U-beams are generally not connected by reinforcement to the cast-in-place concrete of the beam or column, the composite action normally comes from the bond between the roughened inner surface of the precast U-beam and the cast-in-place concrete (Fib-27 2003).

Generally concrete moment resisting frames performed as expected in the Canterbury earthquakes. Modern precast buildings in general did well in terms of ‘life safety’ and ‘collapse prevention’; with the exception of two RC buildings (Uma et al 2013). In the September 2010 Darfield earthquake, modern precast concrete buildings reportedly behaved better apart from experiencing considerable damage to non-structural elements and contents. However, cracking in precast flooring systems due to beam elongation, damage to staircase elements and damage in gravity load elements due to inadequate detailing to cater for the displacement demands were observed in some modern buildings (Uma et al 2013, Kam et al 2010 & Elwood et al 2011). In the February 2011 Christchurch earthquake, the damage to the majority of modern buildings was technically repairable, but many of these buildings were demolished based on financial viability of the available repair options. A full compilation of vulnerability assessment of RC buildings in general in these earthquakes has been reported (Kam et al 2011), but the authors are not aware of any report specific to the damage sustained by the precast building stock.

3 PROPOSED DEMOUNTABLE PRECAST CONCRETE BUILDING SYSTEM

The basic objective of this system is to build a sustainable RC frame building system that can be demounted when/if needed and easily strengthened to meet increased design demand due to change of occupancy or change in design code, and in which damaged structural elements can be easily replaced with new one after an earthquake. In this section, schematic layout of the overall building system, geometric configuration of the steel connections and possible lateral load resisting options within the proposed concept are discussed.

3.1 Schematic Layout

The schematic layout of the proposed demountable precast building system is shown in Figure 2. In this system, precast columns with steel end plate are connected to the foundation through mechanical fix/pin joints; precast beams are connected to the columns using steel angles or steel tubes together with steel plates and pre-tensioned HSFG bolts, precast floor is connected to the precast beam using bolts and steel angles, and the precast flooring elements are connected using steel plate and bolts. The connection between different structural elements and previous research in this type of connection systems are discussed in the following sections.

3.1.1 *Floor –beam connection*

Figure 3 illustrates a typical connection between precast beam and precast hollow-core floor slab using stiffened angle and bolts. The bolt connected to floor slab is removable and the bolt connected to the beam is embedded. The steel angle on beam side is slotted in vertical direction to accommodate relative vertical movement between the beam and slab. Similar type of connection system is also possible with other floor slabs like flat slab, and Tee slab. Negro et al, (2012) investigated structural capacity of non-slotted floor to beam connections using mechanical devices like dowels and couplers and drafted design guidelines for these connections. Details of these connections and their analytical models can be found in literature (PCI design book 2010 & CPCI guidelines 1996). However, to the authors’ knowledge, slotted floor-beam connections have not been explored fully.

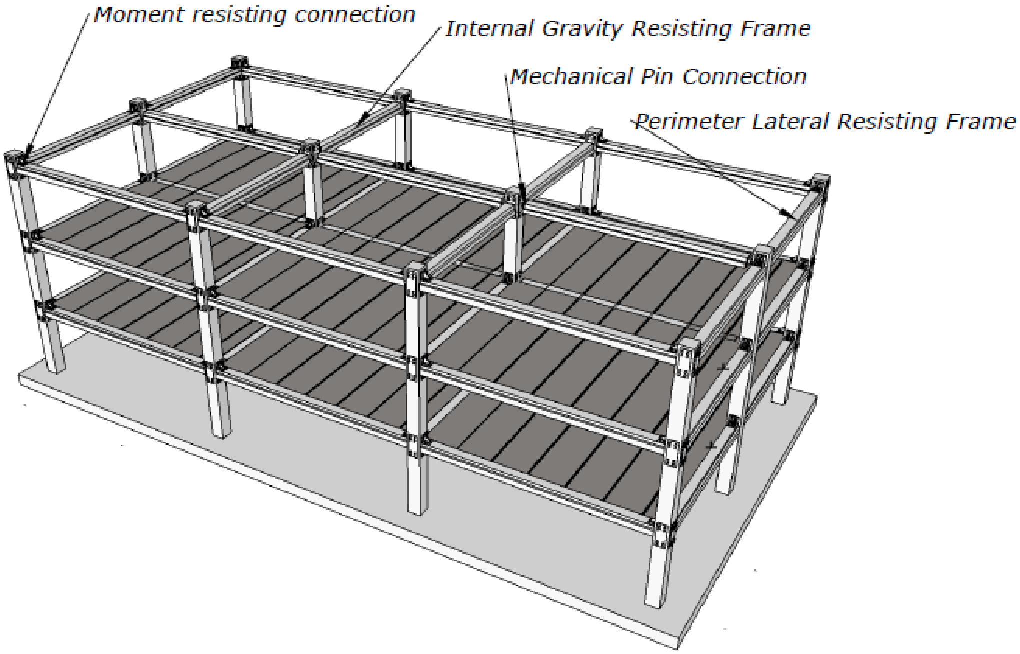


Figure 2. Perspective view of demountable precast frame concrete structural system

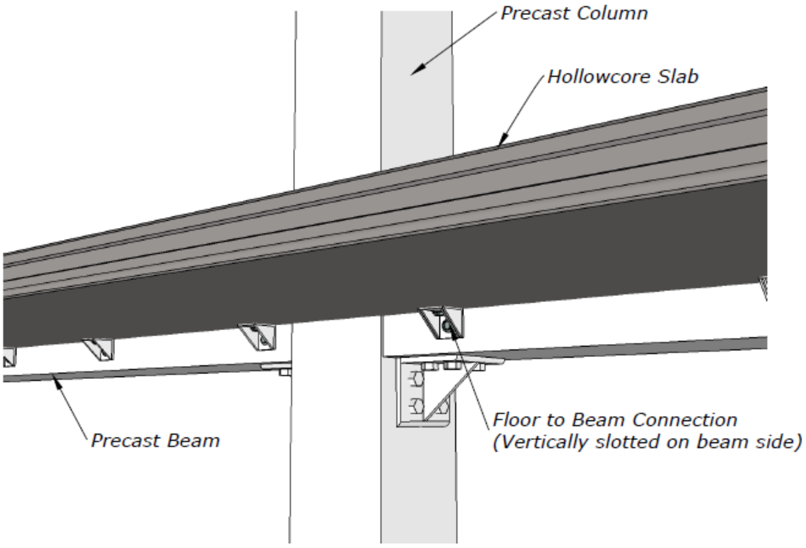


Figure 3. Steel angle connection between hollow core floor slab and precast beam

3.1.2 *Beam-Column connection*

The efficiency of precast concrete frames in resisting gravity and lateral loads relies on the behaviour of beam column connections. Beam-column connections should be designed to transfer all forces. Some connection configurations using mechanical devices are able to transfer only shear and axial forces, these connection systems are called shear connections. Examples of shear connections are corbel connection, and steel insert connection. Experimental results and analytical models of these shear connection systems can be found in literature (Fib-43 2008 & Elliott 1996). There is limited research in development of semi- rigid or rigid connections using mechanical devices. Elliott et al, (2003a) investigated four types of semi rigid beam-to-column connectors; namely welded plate connection, steel billet connection, single cleat connection, and double cleat connection. It was found that although the capacity and stiffness of these connections vary significantly, they can be treated as semi-rigid connection in analysis and design without inducing too much error. Full details of such semi-rigid connections using mechanical connectors can be found in literature (Fib-43 2008). Figures 4 & 5 shows the proposed “strong” dry beam-column connection using stiffened angles or steel tube and HSFG bolts. The bolts are pre-tensioned so that the initial flexural strength depends on the frictional resistance developed between steel surface and concrete surface. Such a connection offers high flexural strength and rotational stiffness to ensure the connection remains in elastic state while the beams (weakest element) reach their capacity. Figure 6 shows a typical mechanical pin connection between a gravity load resisting beam and column, which ensures that the lateral loads are shared only among the seismic frames. This enables the precast frame building system to be built as designed so that no surprising damage is incurred in the gravity frame connection in future earthquakes.

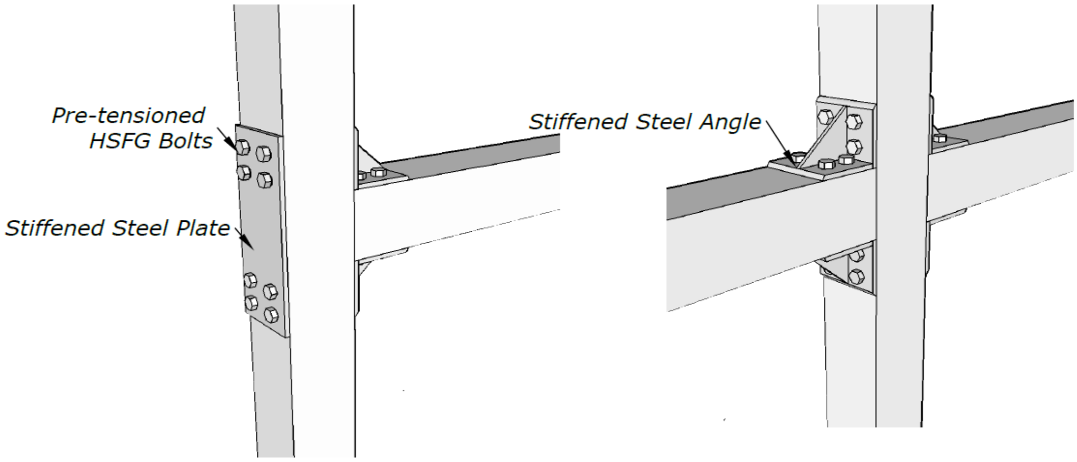


Figure 4. Beam-column connection system using steel angle, steel plate, and HSFG bolts

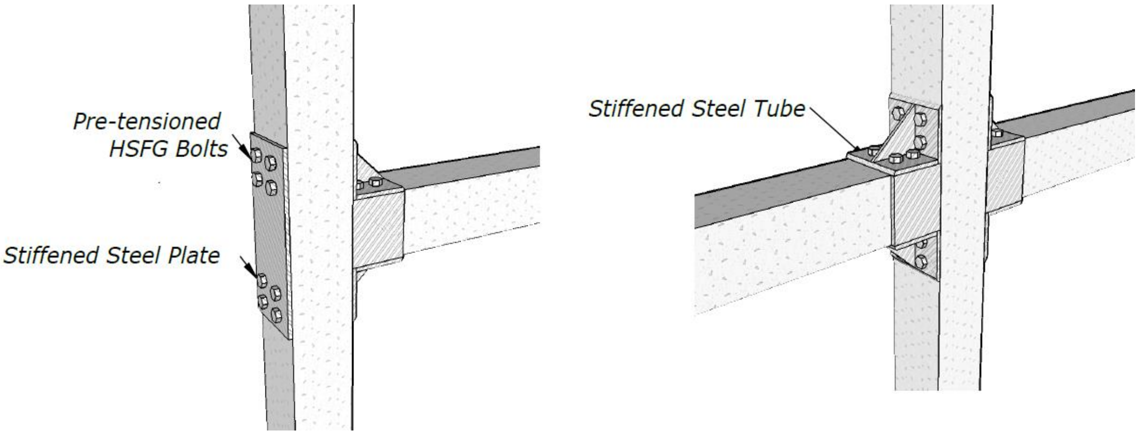


Figure 5. Beam-column connection system using steel tube, and HSFG bolts

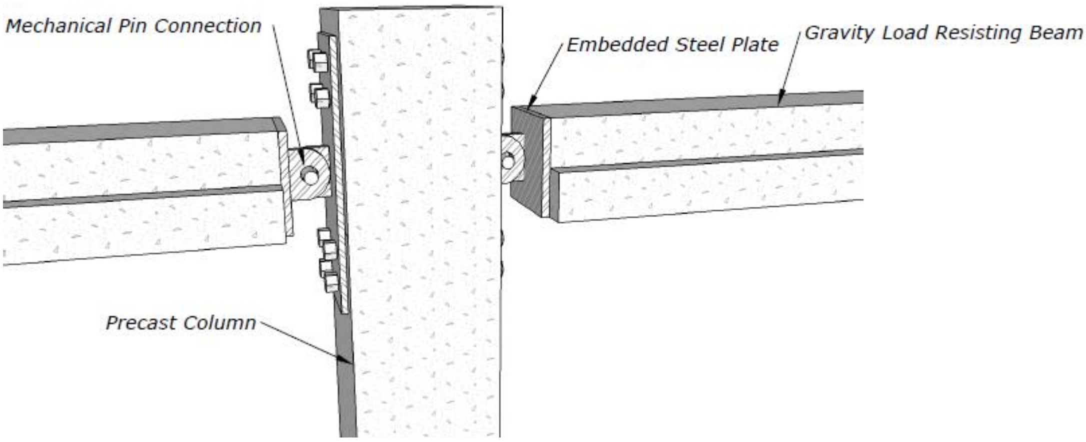


Figure 6. Gravity load resisting beam connected to precast column with use of mechanical pin

3.1.3 *Column-column and Column-foundation connections*

Figure 7 shows a typical column-column connection and a fixed column-foundation connection which uses steel end plate and HSFG bolts. This connection system is also called steel shoe splice connection; they are capable of transferring high tensile force and bending moment, and allow columns to be demounted and removed at any stage. Experimental results and analytical models for this connection system can be found in literature (CPCI guidelines 1996, Fib-27 2003 & Fib-43 2008). Pin column-foundation connection which uses a mechanical pin is also shown in Figure 7. Such pin connections are to be used not just in gravity load resisting frames to transfer shear and axial forces, but they can also be used at the column bases of seismic frames to avoid the otherwise-inevitable damage during earthquakes. This spares from having to replace the columns after an earthquake which can be extremely challenging in tall buildings.

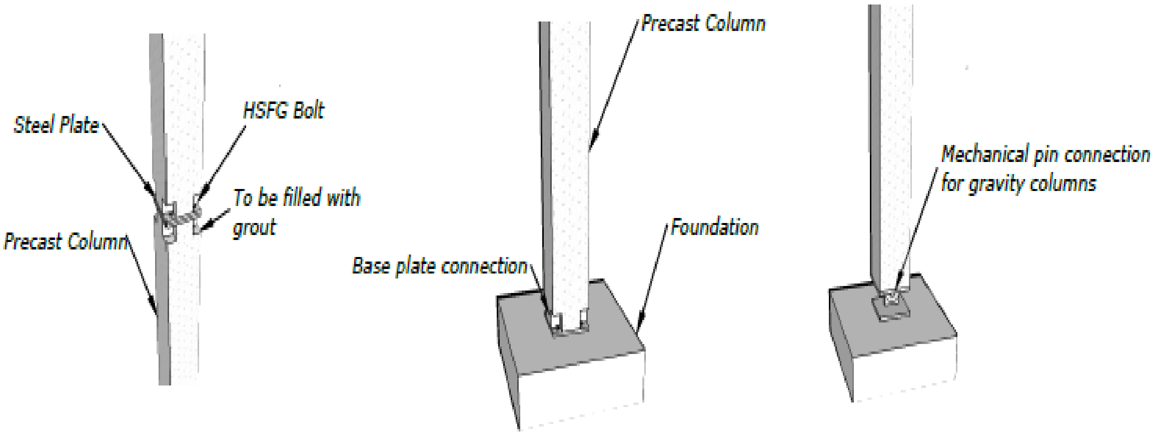


Figure 7. Column-column connection, column-foundation connection using steel end plate and bolts

3.2 **Lateral load resisting system: Available options**

The proposed precast framing system can be unbraced or braced as required to resist the lateral loads. In case of unbraced frames, lateral loads are resisted through flexural behavior of beams and columns whereas in braced frame lateral loads are transferred to foundation through strut and tie action. The column to foundation connection can be designed as fixed or pinned connection depending on the requirement of strength and stiffness. The three structural frame options for resisting lateral loads are: (i) frame with fixed base: (ii) frame with pin base, and (iii) frame with pin base, shear only beam-column connections and diagonal steel braces.

The load path in an unbraced frame with fixed base and pin base under external lateral load is shown in Figure 8. The fixed base frame offers high strength and stiffness compared to the pin base frame. The capacity and stiffness of pin base frame can be considerably increased by addition of steel braces. In a fixed base frame system, ground storey columns will be damaged along with beams in seismic events, and they have to be replaced with new one after seismic events; whereas in a pin base connection only beams (which are easy to replace) will be damaged. The qualitative comparison of base shear capacity between unbraced frames with fixed and pin bases and braced frame with pin base (which can be adopted as an option for new design or strengthening of a pin based frame) is shown in Figure 9.

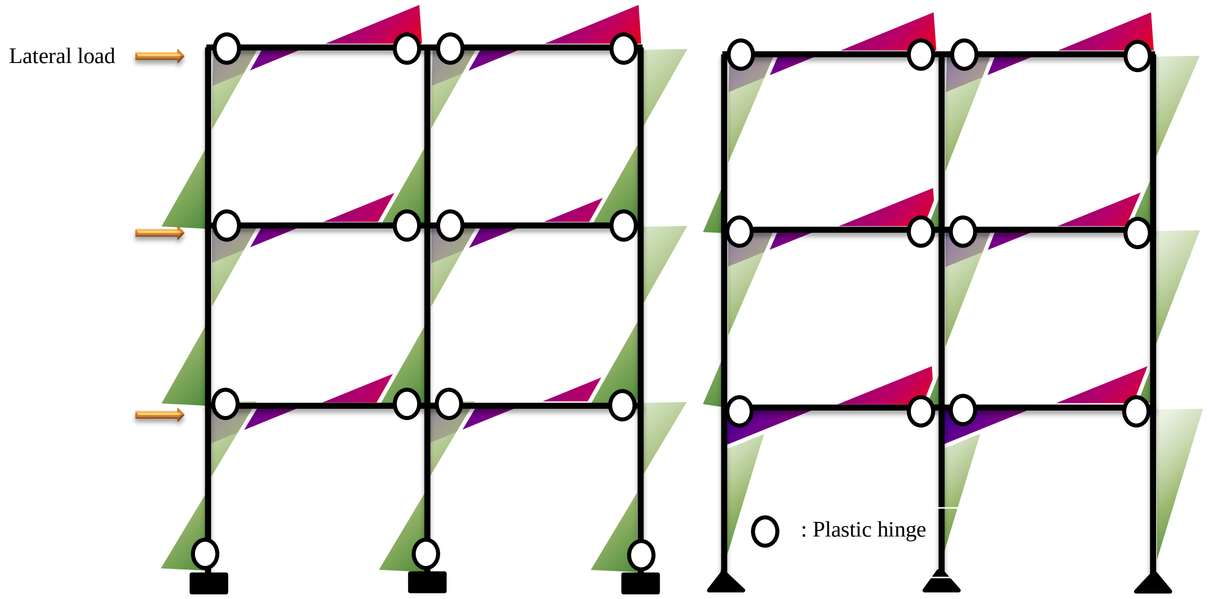


Figure 8. Precast frame with fixed and pin base

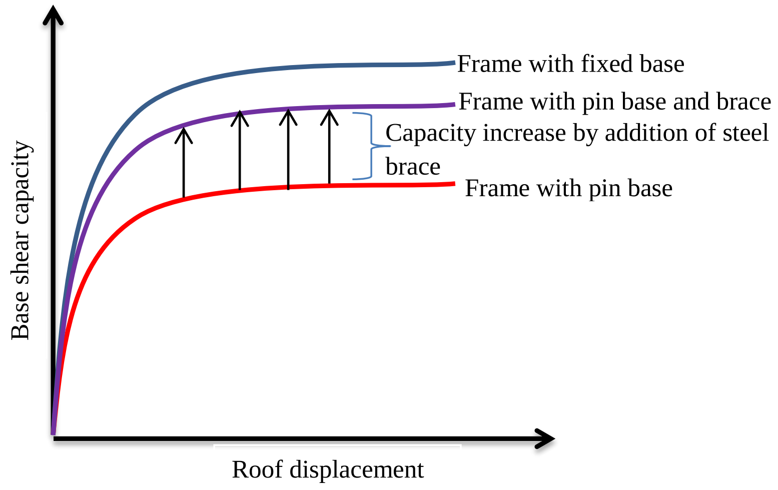


Figure 9. Comparision of capacity with different frame boundary conditions

The third option available for resisting lateral load is to design the system as a braced frame with all frame connections as shear only (i.e. pin) connections as shown in Figure 10. In this system, lateral loads are resisted through strut and tie action in braces. The load path from the roof to the foundation is shown in Figure 10 with colour coded bar. This system can be designed to achieve the strength and stiffness of an equivalent rigid frame with fixed base. Steel braces act as fuse elements in resisting lateral loads. The choice of designing a frame with or without bracing can be left to the designer and the owner depending on the desired plastic hinge mechanism and availability of bays for bracing without disrupting the planned use of the building.

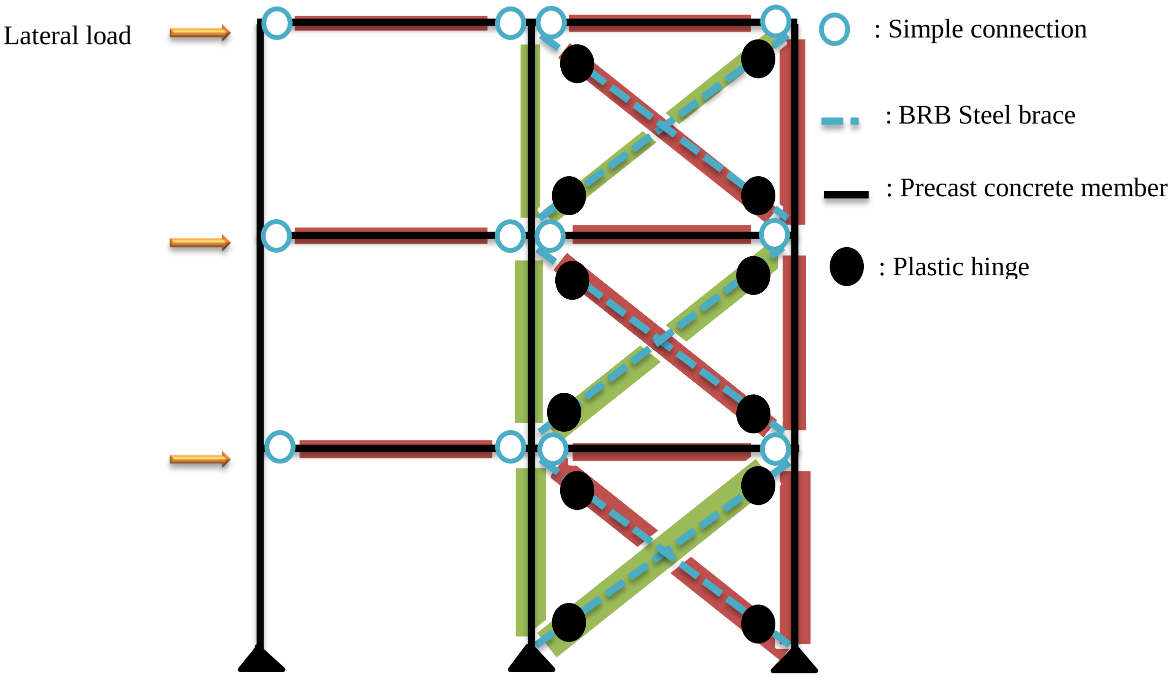


Figure 10. Precast concrete frame with simple connections and Steel brace

3.3 Analytical model of the connection

Capacity design principle should be followed in designing the system; in particular to ensure the “weak-beam strong-column stronger-connection” hierarchy. The load path from the beam to beam-column connection depends on whether the bolts are pre-tensioned or not. It is assumed that the connection capacity is limited by the frictional resistance and shear resistance of the bolts. Other modes of failures like spalling of concrete, crushing of concrete near the bolts, bearing failure of bolts, and bearing, tearing and block shear failures of the steel angle or steel tube can be avoided by proper detailing. The HSFG bolts are pre-tensioned to develop the required clamping force at the interfaces of the elements being joined. The frictional resistance between the concrete and steel surfaces subjected to the clamping force opposes the tendency to slip due to externally applied load. Figure 11 shows the load transfer from the beam to the connection through the frictional resistance. When friction type bolts are designed not to slip under service loads, the design capacity at ultimate load may be calculated as per bearing type connection shown in Figure 12. The bolts in bearing type connection are subjected to shear force and the capacity of the connection is limited by the shear capacity of bolts.

The load transfer mechanism in the beam to column connection when there is no gap between the beam end and the column face is shown in Figure 13. The compressive force from the beam end is transferred to the column as bearing pressure. Flexural strength of this connection is calculated as the product of the shear or frictional resistance of the bolts and the lever arm.

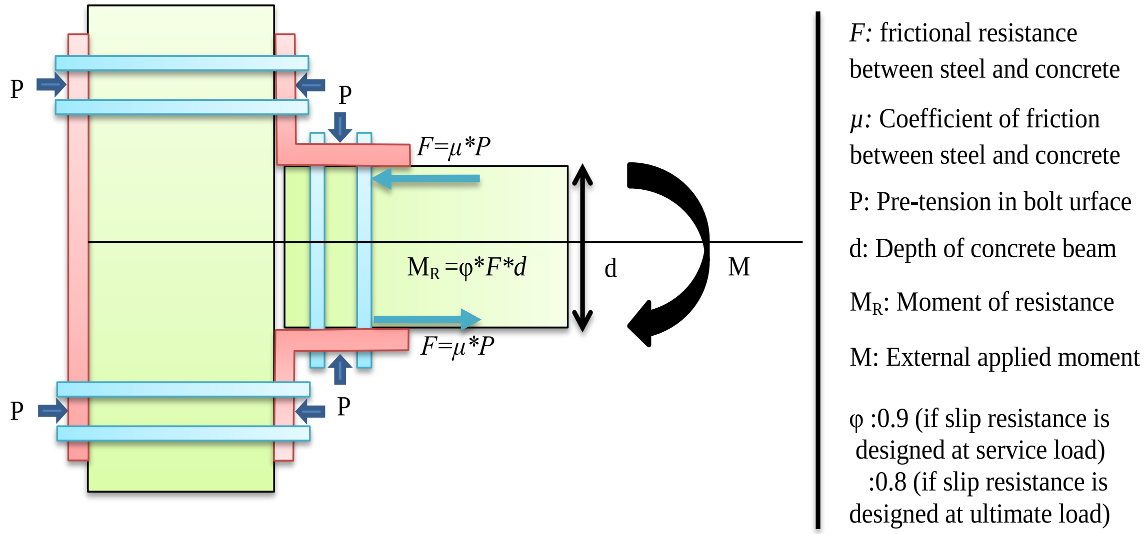


Figure 11. Force transfer mechanism through beam end to column connection (Slip critical connection)

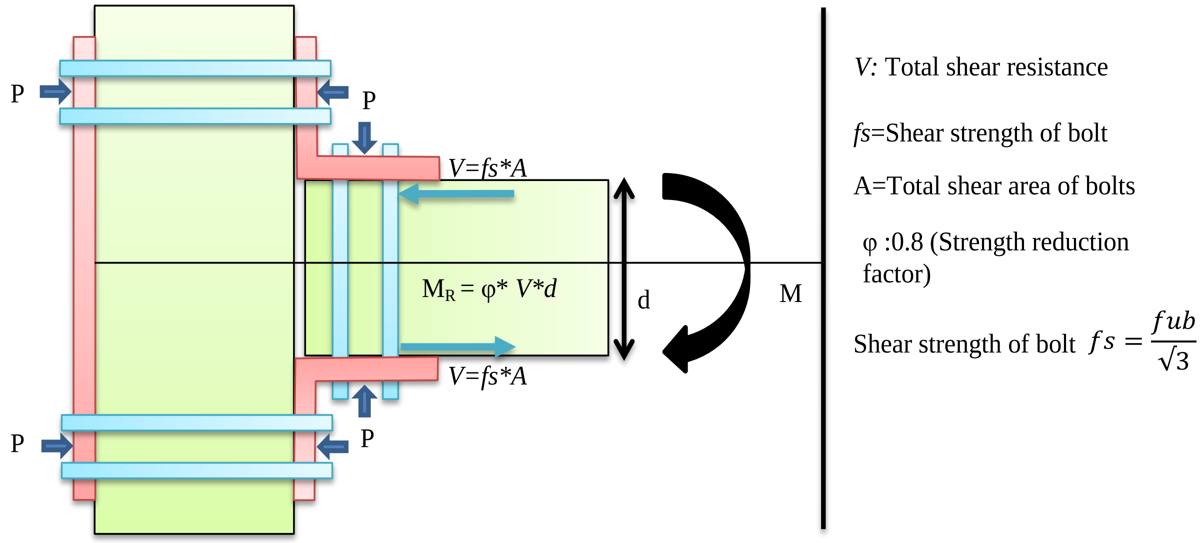


Figure 12. Force transfer mechanism through beam end to column connection (bearing type connection)

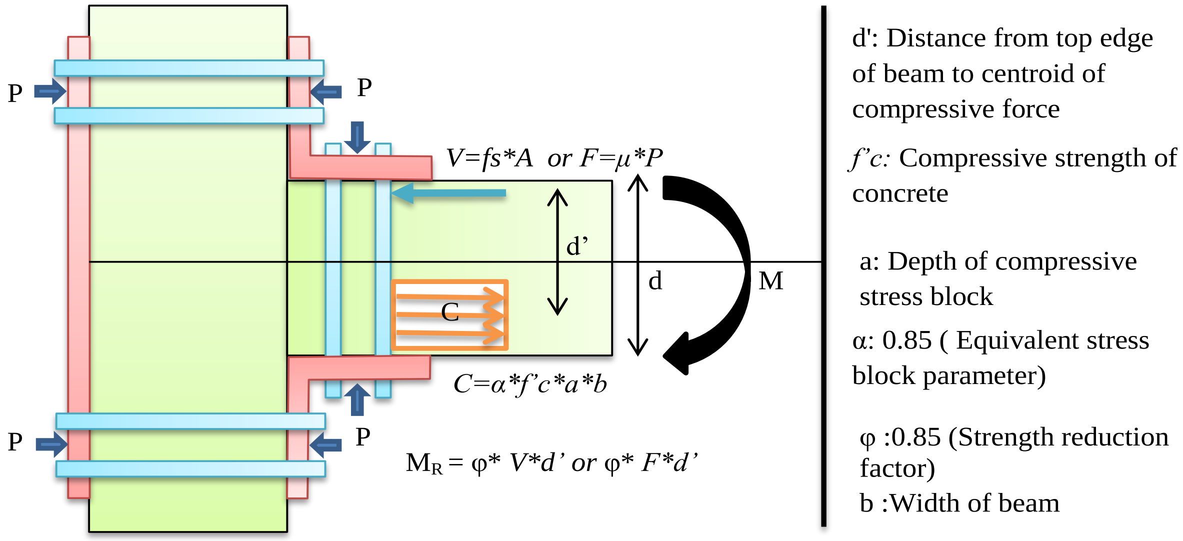


Figure 13. Force transfer mechanism through beam end to column connection (no gap between beam & column)

4 APPLICATIONS

The proposed demountable frame system can be easily implemented in low to medium rise residential, industrial and commercial buildings. Given that majority of buildings in New Zealand are low to medium rise, the proposed system can be adopted in majority of RC frame buildings to be built in future in New Zealand. In addition, because it is easy to demount, the proposed system is perfect for temporary structures like sports complex, parking buildings and storage houses.

Gravity-only frames or secondary elements constructed with current practice have been observed in recent earthquakes to have either participated as part of the lateral load resisting system or deformed in a way similar to (and along with) the main seismic frames. Consequently, damage was inevitable in gravity frames in contrast to the intention of the designer. The proposed system allows gravity resisting frames to be built with mechanical pin connections to the lateral load resisting system. With this practice, the lateral loads will be shared only among the lateral load resisting seismic frames; thereby enabling the building system to be built (and behave) as designed which spares gravity frames from any earthquake damage.

5 LIMITATIONS AND CHALLENGES

The proposed system has to address the following limitations and challenges before being ready for implementing into practice.

1. Difficulty in demounting/replacing damaged beams in upper stories of tall buildings after an earthquake.
2. Practicality of replacing damaged column base in fixed base seismic frames after an earthquake.
3. Lack of design guidelines for the proposed sustainable demountable precast frame building system.
4. Challenges in extending the proposed demountable precast system concept to buildings with RC shear walls.

Research is currently underway at University of Canterbury to find answers to these challenges and to materialize this concept. For this purpose, experimental testing of a range of demountable sub-assemblages and analytical modelling and investigation are being planned to enhance the understanding of seismic performance of such system and to eventually establish design guidelines.

6 CONCLUSION

A new precast concrete frame building system is proposed which inherently offers unique advantages such as; quick construction, simple, demountable and reusable, easily upgradable, quickly repairable to insurance policy compliant condition etc. The proposed system is sustainable and can be easily implemented into practice in all RC frame buildings. It is particularly suitable for temporary structures because the structure can easily be demounted at any time and the components can be reused in another structure. In the proposed precast frame system, damaged structural elements after an earthquake can be easily detached and replaced with a new one; thereby significantly reducing the downtime and rendering it a definitely repairable and low loss solution.

REFERENCES

Bournas, D.B., Negro, P. & Molina, F.J. 2013. Pseudo-dynamic tests on a full-scale 3-storey precast concrete building behaviour of the mechanical connections and floor diaphragms, *Engineering Structures*, 57,609-627

CPCI Design Manual. 1996. Precast and Prestressed concrete, *Canadian Presstressed Concrete Institute*, Canada

Elwood, K.J., Pampanin, S. & Kam, W.Y. 2012. 22 February 2011 Christchurch Earthquake and Implications for the design of concrete structures, *Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, Tokyo, Japan, 1157-1168

Elliott, K.S.1996. Multi-storey precast concrete framed structures. *Blackwell Science*, Oxford.

Elliott, K.S., Davies, G., Ferreira, M.A., Gorgun, H. &Mahdi, A.A. 2003a. Can precast concrete structures be designed as semi-rigid frames – Part 1 the experimental evidence, *The Structural Engineer*, 81/16,14-27.

Elliott, K.S., Davies, G., Ferreira, M.A., Gorgun, H.& Mahdi, A.A. 2003b. Can precast concrete structures be designed as semi-rigid frames – Part2 Analytical equations & column effective length factors. *The Structural Engineer*, 81/16, 28-36.

Fib. 2003. Seismic design of precast concrete building structures.State-of-the-art report, federation internationale de béton, Bulletin 27, Lausanne.

Fib. 2008. Structural connections for precast concrete buildings. State-of-the-art report, federation internationale de béton, Bulletin 43, Lausanne.

Kam, W. Y., Pampanin, S., Dhakal, R. P., Gavin, H. &Roeder, C. W. 2010. Seismic performance of reinforced concrete buildings in the September 2010 Darfield (Canterbury) earthquakes, *Bull. of New Zealand Soc. of Earthquake Eng.*, 43(4), 340-350.

Kam, W.Y., Pampanin, S & Elwood, K.J. 2011. Seismic performance of reinforced concrete buildings in the 22 February Christchurch (Lyttelton) earthquake, *Bull. of New Zealand Soc. of Earthquake Eng*., Vol. 44, no. 4, Dec 2011.

Mohamed, S.A.M. 1992. Behaviour of sleeved bolt connections in Precast Concrete Building Frames, *PhD Thesis*, University of Southampton, UK

Negro, P. & Toniolo, G. 2012. Design guidelines for connections of precast structures under seismic actions, *http://elsa.jrc.ec.europa.eu/publications/LBNA25377ENN.pdf*, European commission.

Park, R. 1990. Precast concrete in seismic-resisting building frames in New Zealand, *Concrete International*, Vol.12, No.11, pp.43-57.

PCI Design Handbook. 2010. Precast and prestressed concrete, 7th edition,Chicago

Restrepo, J.1992. Seismic Behaviour of Connections between Precast Concrete Elements, *PhD Thesis*, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

Uma, S.R., Dhakal, R.P., Nayyerloo , M. 2013.Vulnerability assessment of Christchurch Buildings in Canterbury Earthquakes, *http://www.gns.cri.nz/static/pubs/2013/SR%202013-020.pdf*, GNS Science Report, New Zealand.