STRUCTURAL PRECAST CONCRETE

Skeletal Frame Structures

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Precast concrete construction has managed to remain the least understood of the major forms of multi-storey building construction. This is partly due to the fact that trainee engineers are not exposed to the design requirements and benefits of precast concrete as part of their education.

This limited amount of training and hence questioning of precast design within the consulting engineering profession has resulted in structural precast concrete often being overlooked. Over the last 10 to 20 years manufacturers have promoted their in-house design capabilities and refined their products to widen the use of structural precast concrete. The result is a closing of the gap between complex building design and the perceived limitations of using precast concrete. Structural engineers and architects are now beginning to appreciate the benefits.

Precast structures have been shown to be extremely cost effective, durable, stable, and of the highest quality and strength. Design, due to its specialised nature, often remains with the manufacturers and their personal engineers.

This paper is designed to give further insight into the benefits of structural precast concrete design and construction, with particular emphasis on skeletal frame structures.

1 Suitability of Precast Construction

The misconception that precast construction lacks flexibility is a common reason that it is overlooked right from the design stage. In fact, irregular and challenging architectural designs on many occasions are more suitable to precasting.

Theoretically there are no restrictions on the use of skeletal framed precast construction. Within the Victorian market, for example, it has been found that the niche market for this type of construction is in multi level buildings, where the site can be readily accessed and erection can be carried out by mobile crane.

2 Advantages

Following are brief descriptions on a number of advantages and critical planning issues to consider when using precast.

2.1 Speed of Construction

In our current environment, speed is a critical aspect of any construction project. The use of precast allows not only the speedy erection of the structure, but also flexibility and overall program shortening. This is achieved by allowing the production of components at the same time the footing system is being prepared.

A minimum amount of propping allows the following trades to commence work on the structure earlier than conventional construction methods.

2.2 Off-site Manufacture

The manufacturing of the major components of the building off-site reduces the site labour component dramatically, which in turn, reduces site costs and time.

The erection crew, necessary for precast construction, will usually consist of only about 5-6 people, rather than the several dozen required for in-situ construction.

2.3 Quality Control

Quality control is an ever-increasing requirement in all construction. The production of components off-site, in a factory environment allows each of the facets involved in manufacturing to be strictly controlled, and hence, optimum quality to be maintained.

2.4 Appearance and Finishes

It is widely known that factory produced precast components can be produced with a wide range of finishes. Architectural finishes including colours, surface finishes and carefully moulded surfaces allow the designer considerable flexibility in the overall aesthetic appearance of a structure compared with conventional methods.

3 Critical Planning Issues

3.1 Transportation

One critical aspect of precast construction is the transportation requirement. The erection procedure, and in turn the design of the structure is very much affected by the weight and size of the individual components. The transport of the components is typically by truck and as such, it is imperative to be aware of allowable component sizes and weights. Site accessibility for trucks must also be considered.

3.2 Cranage

The selection of crane type and size is an important ingredient to the viability of the precast structure. Mobile cranes are generally the most economical, with the new generation of high capacity and highly manoeuvrable machines allowing the use of larger components and access to more restricted sites.

On high-rise buildings materials handling can be a critical factor and can have a significant influence on economics. Hence, the higher the building, the longer it takes to lift each component.

4 Precast Design Concepts

4.1 Preliminary Concepts

Probably the most critical aspect of successful precast design is the preliminary evaluation. Each design concept is evaluated to determine the most economical and efficient construction method. The design should be considered as a complete precast system and not simply as numerous individual components connected together.

Prefabrication does not mean to 'cut' an already designed concrete structure into manageable pieces… [Bruggeling & Huyghe]
The best result is obtained when the method of construction is evaluated as part of the design concept. The structural options to be considered include:

- ***Panelised structural envelope***. This type of structure generally comprises structural precast walling and/or exposed spandrel beams and panels with the floor system spanning between walls.

- ***Structural precast skeletal frame***. This type of structure incorporates a structural precast frame of columns and beams with a precast floor system. The frame can be either moment resisting or pin jointed with lateral loads carried by shear walls.

- ***Hybrid structure***. This term has been coined in Europe to describe combination structures that incorporate precast concrete combined with other structural materials. For example a structure with precast flooring supported on a steel frame or masonry walls.

- ***Combination structure***. As the name suggests a building combining more than one of the above systems.

The first task, in precast design, is to establish the most economical geometric layout by minimising the number of components. The cost of components should be considered, with the objective being to minimise the number of high cost components, and maximise the number of low cost components.

The optimum solution is generally found in a rectangular grid. The most economical solution, unlike traditional construction techniques, is usually found with the precast floor system spanning the longest dimension. This is due to the fact that with precast floors and in particular hollowcore systems the cost penalty of increasing the slab span from 8m to 12m is virtually insignificant. On skeletal frame structures this allows supporting beams to span the shorter dimension and the beam depth to be minimised. It must be stressed, however, that the most economical solution is very much project defined and must be evaluated on a job-by-job basis.

4.2 Design Evaluation

When considering the design models for this type of construction it is critical to evaluate the stability and safety of the structure during all phases of construction. With cast in-situ structures, the stability of the structure is generally not a critical aspect. With a precast structure, overall stability is not achieved until the connections are activated. It is, therefore, essential as part of the design evaluation to consider the stability of the structure not only in the final stage, but also during erection.

The design of the horizontal stability of a structure requires consideration of the method in which wind and other imposed loads can be transferred to the footing system. In its final form the entire structure must be designed to ensure overall stability. Stiff stabilising components that are able to transfer horizontal loads to the footing system are vital for ensuring stability of the structure.

There are a number of methods in which stability can be achieved depending on the particular structural type being considered. For the various structural types these include;

- ***Panelised structural envelope.*** The precast walling carries lateral loads acting as shear walls. Floor systems are designed to act as horizontal diaphragms to transfer horizontal loads to the shear walls.

- ***Structural skeletal frames.*** For a moment resisting frame, lateral loads are carried by classic frame action. For pin-jointed frames, shear walls, stair or lift shafts acting as shear resisting elements carry lateral loads. Floor systems are again designed to act as horizontal diaphragms to transfer horizontal loads to the shear walls.

- ***Hybrid and combination structures***. Lateral resistance on these types of structures will generally be provided by either frame or shear wall action depending on the predominant type of structure.

Generally, shear walls are the most effective and economical method of providing stability for low to medium rise buildings. Most buildings have lift or stair shafts that can readily be used as shear walls. These shear walls are typically designed as deep beams or box structures cantilevering from the footings. While the floor systems are designed to act as horizontal diaphragms to transfer horizontal loads to the shear walls.

Providing full capacity moment or torsional connections between structural components to generate frame action is expensive and rarely warranted. These systems are more commonly used in high risk earthquake areas where design codes require a certain percentage of the lateral load to be carried by ductile moment resisting frames.

Lateral loads carried by cantilever action of precast columns or walls are sometimes an economical option for one or two storeyed buildings. These columns or walls are designed to cantilever from the foundations with a moment resisting connection to provide overall structural stability. This system is frequently used to comply with the BCA requirement for post-fire stability of external walls

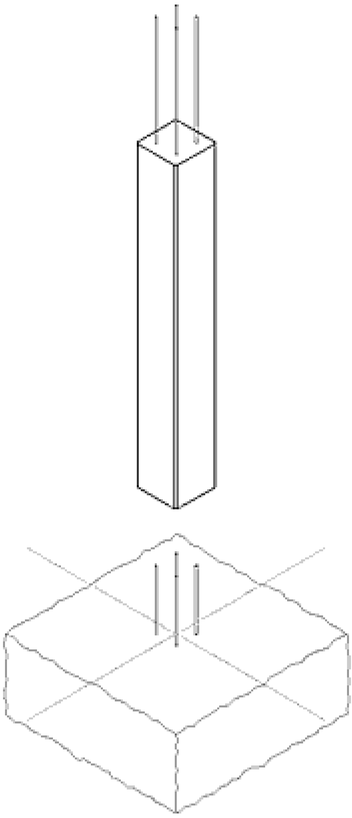
5 Componentry

While the types of components that can be produced and effectively used within this form of construction are only limited by the imagination, one of the significant reasons that precast has become such a successful form of construction has been the ability to standardise a number of components.

Standardisation is often misconstrued as modulation. Standardisation typically refers to construction techniques and section types rather than a specific unit. For example, two completely different structures can be designed and erected using standardised products simply by adjusting beam depths, column lengths, wall panel positions and different floor systems

As there are many different forms of precast componentry, this paper will focus on those that have made a significant impact on shaping the Victorian market.

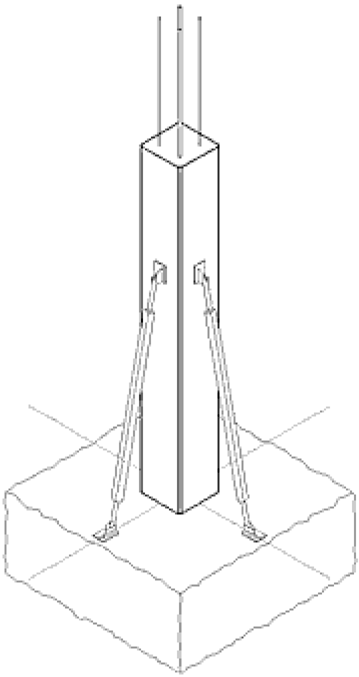
One of the most significant reasons for the evolution of the following concepts has been the consideration of labour verses material costs. This has resulted in an emphasis on simplicity and repetition, even at the expense of material costs, to ensure labour productivity is maintained at the optimum level.



COLUMN POSITIONING AND PROPPING 1

5.1 Columns

Precast columns can be produced as either multi-storey corbelled columns or single floor to floor elements. They may be either prestressed or reinforced. In the Melbourne market it has been found that the single floor to floor column is the most economical. Single storey reinforced columns are simple to design, detail and construct. Once loads and bending moments are established the design process is the same as a standard reinforced in-situ column. Eccentric loading due to erection requirements and localised effects at the top and bottom of the column should be taken into account in the design. Extra reinforcement is usually provided at the top and bottom of the column, these additional ties act as anti-splitting reinforcement

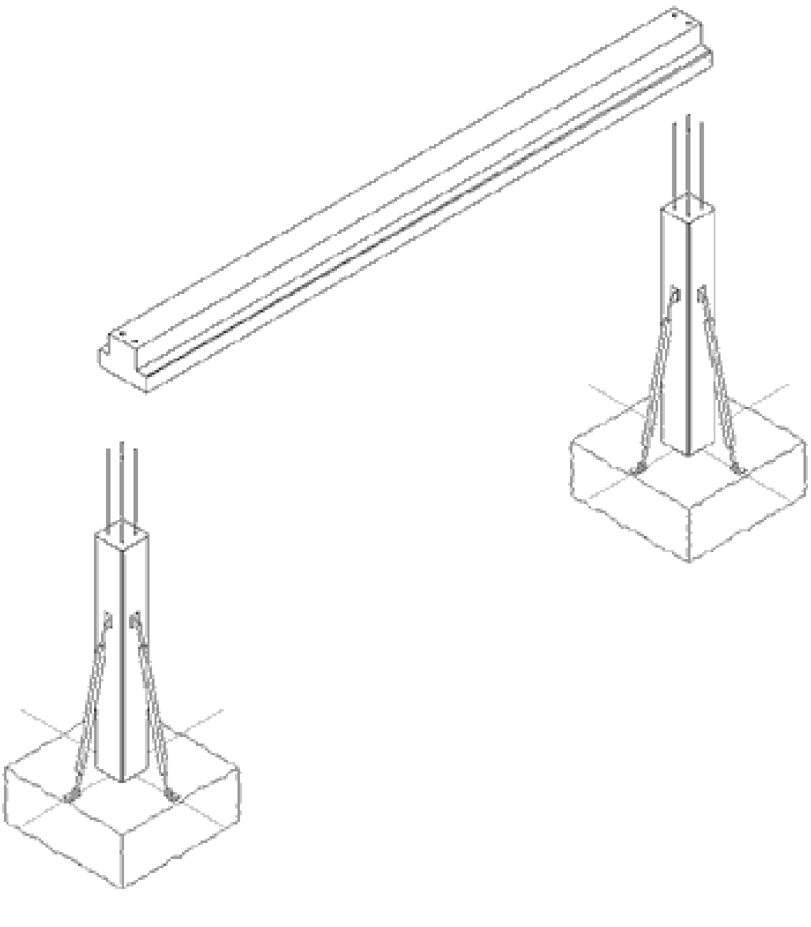


Other important factors that must be considered in designing include the required beam bearing on the column. When considering this bearing area, it must be remembered that due to the corner chamfer and backing rod to dam the high flow grout, approximately 30 to 40 mm is lost around the perimeter.

The base connection is generally analysed as a pin joint and due to connection details the columns tend to be conservatively sized, manufactured with high strength concrete, and reinforcement typically limited to four corner bars with nominal ties. This approach results in extremely simple components that can easily be mass produced.

5.2 Beams

Precast beam details have been developed with simplicity and practicality in mind. Typically they are an inverted Tee profile and are designed as prestressed or partially prestressed. This type of component is designed as continuous for imposed loads in its final form, while being simply supported during the erection phase. They are also designed so that no propping is required during erection of the supported floor. The precast floor components sit directly on the ledge of the inverted Tee.



With floor to floor height columns the beams are able to sit directly on top of the columns. Dowels protruding from the columns pass through ducts within the end of the beams to provide the pin joined connection. This allows the connection between beams and columns to be very simple and eliminate the need for difficult corbelled or mechanical shear type connections.

BEAM POSITIONING ON COLUMNS 1

One of the most critical design cases for the beams and the beam to column connection is the design for torsion loading. During the erection phase it is inevitable that at some stage the beam will be loaded on only one side causing the beam to 'roll' on the column particularly if the column is narrower than the beam. The beam column connection must be designed and detailed to resist this torsional load.

While the use of this type of one way skeletal structure is a very simple and effective method of construction, it does require a slightly increased overall beam depth compared to slim line profiled beams or a traditional band beam system. The end result is generally that it is more economical to increase the overall building height than to reduce beam depths.

5.3 Precast Floor Systems

There are numerous precast flooring components to choose from, including:

- Hollowcore slabs
- Composite Beam / Slab (Ultra floor / Transfloor)
- Composite Prestressed Planks (MiniSlabs)
- Single and Double Tee components

Although interchangeable, to some extent, each of these forms of flooring has an optimum span range. This optimum range depends not only on direct cost but indirect costs such as any requirements for temporary propping during erection and the method of support or connection to beams.

The skeletal frame systems, discussed in this paper, are based on the use of hollowcore slabs. These slabs are precast, prestressed concrete units with continuous voids formed to reduce weight, and in turn, cost.

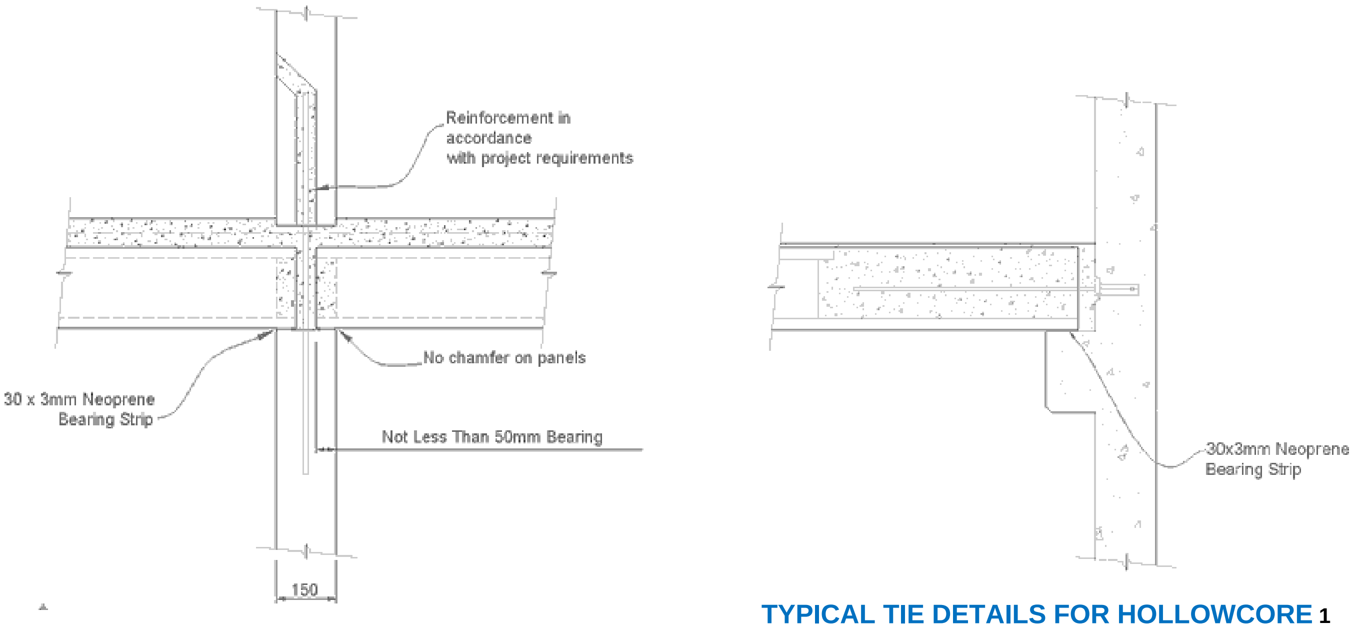
Hollowcore slabs are manufactured on long line casting beds (over 100 metres in length) and saw cut to the required length after curing. There are two distinct manufacturing methods. A dry cast extrusion system in which a very low sump concrete is forced, or extruded, through a machine or a wet mix method in which a higher sump concrete is poured in two or more layers by a machine similar to a large kerb and channel machine.

Using these sophisticated manufacturing systems, hollowcore slabs are highly efficient, and due to the optimised profiles, are able to achieve span to depth ratios that other methods cannot compete with.

While hollowcore units have multiple uses in Melbourne, as wall panels, spandrel panels and bridge deck units, they are predominantly used as floor or roof deck systems

Hollowcore slabs are generally designed as simply supported, as it is more economical to provide all the strength in the positive moment area than to generate both positive and negative moment capacity. Shear capacity can become a critical case where high negative moments are activated. In these instances one or more cores may need to be opened and filled with concrete. Cantilevers can be achieved up to normal span to depth ratios by the simple addition of top strands.

To tie the structure together and help provide diaphragm action in the floor system hollowcore slabs are usually topped with a structural screed. The optimum thickness of the screed is about 60mm. The prestress induced hog in the slabs needs to be taken into account in setting the thickness



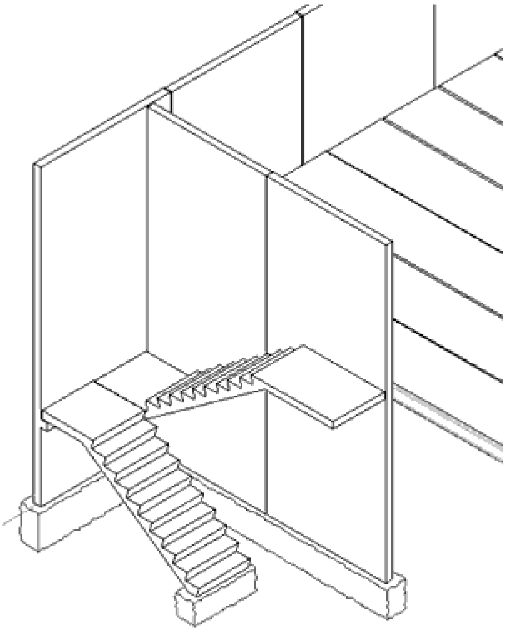
TYPICAL TIE DETAILS FOR HOLLOWCORE 1

5.4 Stair Flights

While precast stair flights have been extensively used throughout Europe and the UK, they are still in their infancy in Australia.

Precast stair flights are manufactured to incorporate the stair flight and landings as a prefinished product. They are designed in a similar fashion to standard in-situ stair flights and landings with special attention required in the detailing and connections.

These units are becoming increasingly popular due to the flexibility they provide on the building site. By giving immediate access to the construction level they can reduce or completely eliminated use of temporary access towers



STAIR FLIGHTS

5.5 Other Components

Other components that are often incorporated into precast construction include items such as solid structural wall panels, precast balcony units, spandrel beams and other variations to those already mentioned. They are commonly used in combination with the more basic panelised or skeletal frame structures.

5.6 Connections

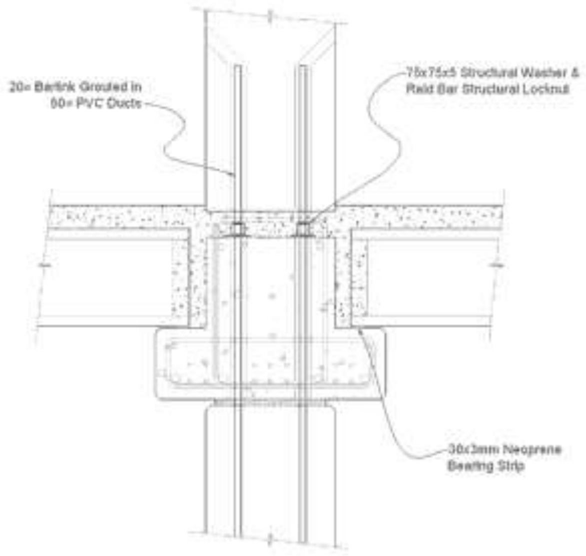
The emphasis on connection design is simplicity. The main objective is to provide a connection that serves as many functions as possible while being simple and quick to secure. The simplest way of meeting this objective is to design precast structures with pin jointed connections.

The footing to column connection typically takes the form of dowel bars projecting from the footing with matching cast in grout tubes in base of the column. This allows the column to be lowered directly over the dowels onto preset levelling shims. The dowels act firstly as locating pins, and secondly, as a pin joint when the grout tubes and base are fully grouted.

The column to beam connection is usually made up of dowels projecting from the top of the column over which the beam, again with matching grout tubes, can be lowered directly onto preset levelling shims on the column. As there is a likelihood that the beam, either during erection or in service may be subject to uneven loading a course thread bar (such as a Reid Bar) is used as the dowels. This threaded bar then allows the use of nuts and washers to clamp the beam to the column and in most cases eliminate the need for propping of the beam.

By using this type of connection the dowel can be projected above the top of the beam to enable the next level of column to be erected in a similar fashion to the footing to column connection.

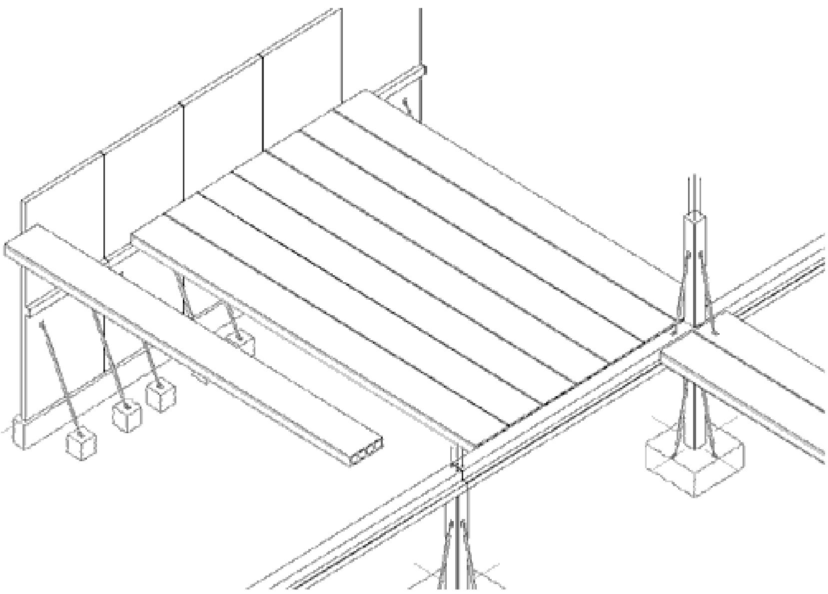
The grout tubes used for the connections are kept reasonably large (typically 50mm diameter) to allow the use of high flow grout rather than requiring pressure grouting.



COLUMN TO BEAM CONNECT

6 Design for Erection

For precast concrete construction there are two distinct design phases. The first is the traditional structural design of the building for the in-service conditions. The second is the design for erection. This second stage is entirely dedicated to the design for handling, transportation, and erection of individual components, and the structural stability of the building throughout the erection process.



In addition to the normal design considerations, precast components must be designed for additional loads that they may be subjected to during erection. These include handling and transportation loads, erection loads, wind loads on elements while only in braced position and construction loads.

In simplistic terms, the erection design involves working out on paper how a particular building is to be built. This requires the project engineer, builder, precaster and the erector to plan the complete construction sequence. It is at this point that access restrictions, cranage limits, component size and weights, and the builders construction requirements become the defining factors as to what is the most appropriate method of construction.

Due to the significant amounts of precast construction within Victoria, WorkCover Victoria has published a new Industry Standard, "*Precast and Tilt-up Concrete for Buildings*". This standard has been developed in conjunction with representatives from within the Building Industry, Industrial Unions, as well as the Victorian Workcover Authority. While the Industry Standard is not intended to be an all-encompassing design, manufacture and erection manual, it does provide practical advice on safety issues related to the design, manufacture, transportation and erection of precast components. Although it is written to be compatible with Australian Standards, where these Standards setout minimum requirements, the Industry Standard explains how to attain those minimum requirements, within a safe working environment.

One of the main themes throughout the Industry Standard is the assigning of responsibility for each phase of the work. For erection the Industry Standard requires a detailed Work Method Statement to be documented, complete with an erection design. The Work Method Statement is the responsibility of the builder and precaster, and the erection design is nominated to be the responsibility of the Erection Design Engineer. This is a person qualified for membership to the Institution of Engineers and who is experienced in the field of structural engineering. They will usually be responsible to the builder or the precaster and, while it is often the case, the Erection Design Engineer may or may not be the project consultant. The purpose of these requirements is to ensure that the erection of precast buildings is 'engineered' and fully documented and is not something that the erector sorts out when the crane arrives on site.

The design for erection should take into account the agreed erection sequence and detail the bracing requirements at each stage of the process. Bracing is the critical operation during precast erection and the Industry Standard covers this in some detail. Considerable concern has been raised within the Industry, in Melbourne, over the types of brace fixings being used and the Victorian WorkCover Authority have recently issued a number of 'alerts' for guidance in the most appropriate types of fixing.

As well as documenting the sequence in which components are to be erected, the Work Method Statement should set out the additional work that must be completed prior to advancing to the next stage of erection. Tasks such as grouting, jointing or screeding and any other specific requirements relating to the stability of the structure during erection must be detailed.

7 Conclusion

Precast concrete in Melbourne is far from a new phenomenon. Throughout its evolution it has developed from simple modular components, through to fairly complex designed components that are still simple to manufacture and erect. The idea of standardisation rather than modulation has enabled the use of easily produced components in architecturally challenging designs.

Apart from safety, the most critical aspect of successful precast construction is the initial concept. To maintain all the advantages and reduce the limitations it is imperative that the project be designed as a precast structure from the outset.

'It is very important to realise that the best design for a precast concrete structure is arrived at if the structure is conceived as a precast structure from the very outset and is not merely adapted from the traditional cast in situ or masonry methods.'
[FIP Commission, 1998]

The growth in the precast concrete market, within Melbourne, has been such that the Victorian Government has seen the need for an Industry Standard to regulate safety issues associated with this type of construction. The introduction of this Industry Standard is a positive move that will ensure that correct procedures are followed for all facets of the design and construction of Precast Concrete.

8 Bibliography

Bruggeling, A.S.G. & Huyghe, G.F. (1991) *Prefabrication with Concrete*, Balkema, Rotterdam.

Elliot, K.S. (1996) *Multi-Storey Precast Concrete Framed Structures*, Blackwell Science Ltd., Oxford.

Federation Internationale De La Precontrainte (1998) *Planning and Design Handbook on Precast Building Structures*, FIP Commission on Prefabrication, SEKO Ltd., London.

Federation Internationale De La Precontrainte (1988) FIP *Recommendations: Precast Prestressed Hollow Core Floors*, FIP Commission on Prefabrication, Thomas Telford, London.

Precast / Prestressed Concrete Institute (1998) *Manual for the Design of Hollow Core Slabs (2nd Edition)*, PCI, Chicago.

Victorian WorkCover Authority (2001) *Industry Standard: Precast and Tilt-Up Concrete for Building*, Victorian State Government, Melbourne.