bulletin 19

state-of-art report

fib CEB-FIP

Precast concrete in mixed construction

Precast concrete in mixed construction

State-of-art report prepared by

Task Group 6.3

June 2002

Subject to priorities defined by the Steering Committee and the Praesidium, the results of *fib*'s work in Commissions and Task Groups are published in a continuously numbered series of technical publications called 'Bulletins'. The following categories are used:

category	minimum approval procedure required prior to publication
Technical Report	approved by a Task Group and the Chairpersons of the Commission
State-of-Art report	approved by a Commission
Manual or Guide (to good practice)	approved by the Steering Committee of *fib* or its Publication Board
Recommendation	approved by the Council of *fib*
Model Code	approved by the General Assembly of *fib*

Any publication not having met the above requirements will be clearly identified as preliminary draft.

This Bulletin N° 19 has been approved as a *fib* State-of-art report in spring 2002 by *fib* Commission 6 *Prefabrication*

The report was drafted by *fib* Task Group 6.3 *Precast concrete in mixed construction*:

Kim S. Elliott (Convenor, United Kingdom)
Sven Alexander (Norway), Bruno Della Bella (Italy), Charles Goodchild (United Kingdom), Izzo (Italy), Anumolu Ramakrishna (India), Nordy Robbens (Belgium), Harry Romanes (New Zealand), Ladislav Sasek (Czech Republic), Arne Skjelle (Norway), Arto Suikka (Finland), Jan A. Vambersky (The Netherlands)

Full affiliation details of Task Groups members may be found in the *fib* Directory or on *fib's* website http://fib.epfl.ch.

Cover picture: Mixed construction using precast concrete and timber (Courtesy Spenncon, Norway)

The publication of this report in colours has been made possible through the generous support of these sponsors: The Consulting Engineers Group Inc. (USA), Dycore B. V. (The Netherlands), Parma Betonila (Finland), Concrete Manufacturers Association (South Africa), Larsen & Toubro Ltd - ECC Construction Division (India), Bundesvereinigung der Pruefingenieure fuer Bautechnik (Germany), VBI Verenigde Bouwprodukten Industrie BV (The Netherlands), Spenncon A/S (Norway), PCI Precast / Prestressed Concrete Institute (USA), Generali Prefabbricati SPA (Italy), Intemac (Spain), Precompressi Centro Nord (Italy), Addtek R&D (Finland), CSP Prefabbricati (Italy), Deltatek Oy (Finland), ERGON (Belgium), IPHA (United Kingdom), PCE Engineering (Finland), Ronveaux (Belgium), AB Strängbetong (Sweden), Trent Concrete (United Kingdom)

First published 2002 by the International Federation for Structural Concrete (*fib*)
Post address: Case Postale 88, CH-1015 Lausanne, Switzerland
Street address: Federal Institute of Technology Lausanne - EPFL, Département Génie Civil
Tel (+41.21) 693 2747, Fax (+41.21) 693 5884, E-mail fib@epfl.ch, web http://fib.epfl.ch

ISSN 1562-3610
ISBN 2-88394-059-2

Printed by Sprint-Digital-Druck Stuttgart

1 Introduction to mixed construction

1.1 Scope of the publication

The purpose of this publication is to show how precast concrete may be mixed in combination with other structural materials to maximise overall building performance. The other materials are:

- cast insitu concrete, reinforced and post-tensioned;
- structural steelwork;
- timber and glue-laminated timber;
- masonry in brickwork and blockwork;
- glass and glazing.

The new airport terminal building near Oslo in Norway, Fig. 1-1, exemplifies this approach with a mix of precast concrete, steelwork and glue laminated timber in the superstucture, and cast *insitu* concrete and glass curtain walling elsewhere.

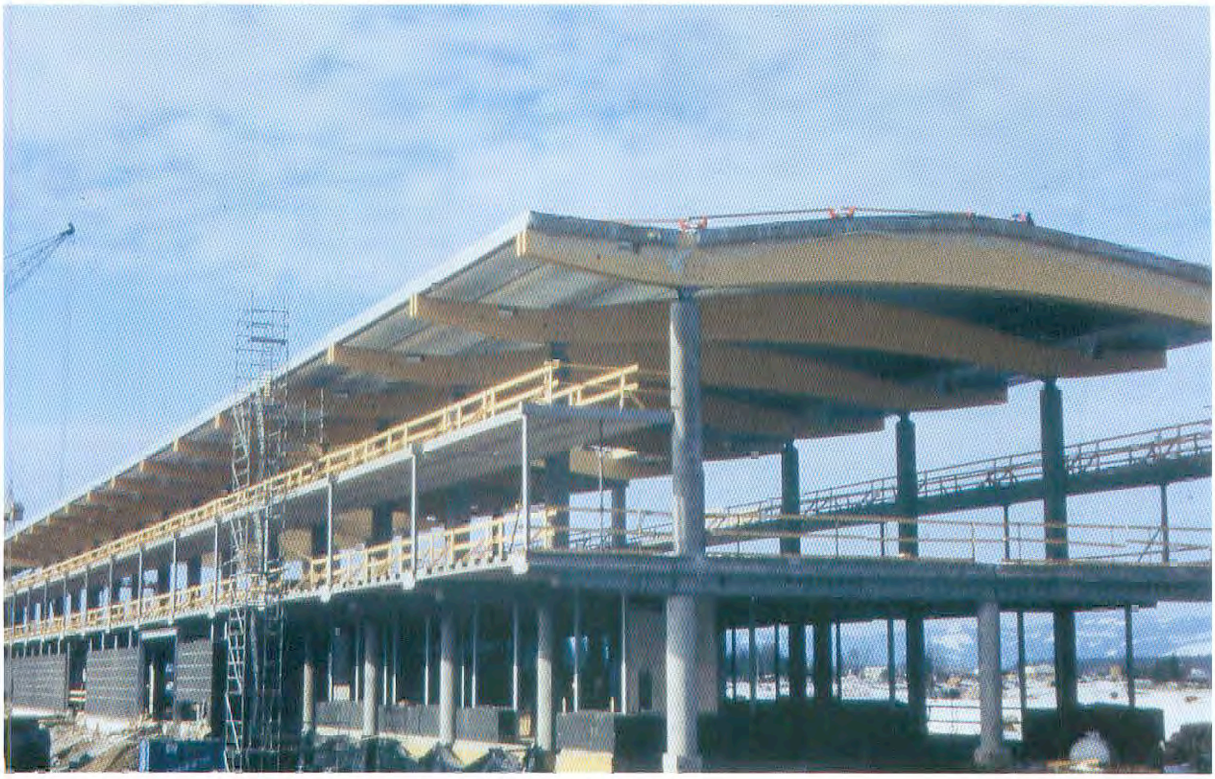


Fig. 1-1: Mixed construction using precast concrete and timber, both indigenous materials to the local construction industry in Norway (Courtesy Spenncon, Norway)

The aim is to provide a companion volume to *Composite Floor Structures* [FIP, 1998] and to show some of the many other ways that precast concrete can be used to advantage with other materials. The term *mixed precast construction* is used to describe these other combinations.

The intention is not to discuss the design calculations - that is for a future '*fib* Guide to Good Practice'. It is meant as a *'State-of-the-Art'* publication showing photographs, sketches and details of precast concrete with other materials. There are no design equations, although some technical information on how to combine the materials, e.g. bearings, connections, tolerances, thermal and shrinkage effects, etc., is included if appropriate.

Although precast concrete is a versatile material and has been used in may varied situations it might be limited in one of several ways. The most common of these are:

1) lightly loaded roof structures, where the favourable bending and tensile properties of steel and timber trusses perform best,
2) in providing a continuous (visually unbroken) envelope or facade in, for example, brick masonry, thin steel sheeting or glass curtain walling,
3) in completion of the interior of buildings where insitu brickwork or blockwork infill panels might be used either as partitioning or as lateral bracing in the structure,
4) in non repetitive elements with non standard fixings, or where moulding costs are a significant proportion of the total cost of an element.

This document considers the various ways in which the performance of precast concrete may either be enhanced, from a structural and / or architectural point of view, or complemented by the addition of other materials. Fig. 1-2 shows how slender structural steel columns have been laterally braced by precast concrete walls in a very lightweight office building. In fig. 1-3 the prefabricated brickwork pillars support arched precast concrete floors, both of which are expressed as architectural features.

Fig. 1-2: Mixed precast concrete and structural steelwork

Fig. 1-3: Precast concrete floors and brick pillars form both the structural elements and the architectural façade.

This is the more typical usage of precast concrete in mixed construction because of the manner in which precast concrete can be moulded to give plain or sculptured surfaces, and its excellent durability, fire resistance and dimensional accuracy. However, of paramount importance to modern day construction is the rapid speed of construction that alleviates site programming difficulties for the following trades.

More design and build contracts are using a wider range of subcontractors who hold no prejudice for or against certain types of construction. This is one of the reasons why precast concrete has been successful in mixed construction during the past 20 years. The list of alternative forms of construction, and some of the details used to make each design a success, are not exhaustive, but they do present those in which precast concrete can be utilised most favourably.

The document focuses on the use of mixed construction in multi-storey buildings, offices, housing, grandstands, parking garages, and industrial warehouses, etc. It focuses on precast concrete as the main construction material and looks at the manner in which other materials can be integrated with precast concrete, such as:

- structural steelwork and timber roofs on precast frames;
- precast floors onto steel and concrete beams, and masonry walls;
- profiled metal decking on precast beams;
- precast frames onto cast insitu foundations, retaining walls etc;
- precast frames stabilised by masonry walls, steel bracing etc;
- precast cladding in steel or cast insitu frames, and the reverse;
- glass curtain walling, stone cladding or metal sheeting onto precast concrete frames etc.

Chapter 2 shows several ways in which precast concrete can be combined with cast insitu concrete, often termed *hybrid* construction [Goodchild, 1995]. Although cast insitu will slow down site progress it is mostly used to form homogenous connections between precast elements and provide a structural topping for horizontal diaphragm action. In other cases it is used to form the foundations and sub-structure to the building.

Chapter 3 considers the many options available with structural steelwork. The focus is largely on the use of long span prestressed concrete floors supported on rolled and prefabricated steel beams. There are many examples of using steel roof trusses in warehouses, offices and stadia.

Chapter 4 looks at the emerging technology of combining timber, specifically long span glue-laminated beams and rafters, with precast concrete. Precast floors are used to replace timber floors in timber frame construction. There are several cases of where precast walls are combined with timber flooring for housing.

Chapter 5 illustrates the many obvious, and less obvious, combinations of brick and block masonry with precast concrete structures and floors. Although the most common combination is to use prestressed floors on load bearing walls. this contrasts with multi-storey masonry pillars supporting vaulted precast floors and steel rafters found in other exiting projects.

The strengths and weakness of each material studied are assessed as part of the total building design. In some cases it is obvious that the load carrying performance of one material outweighs another. In other cases aspects such as thermal, fire, vibration, fatigue, creep, acoustic, seismic and visual characteristics, and the geographical local availability of that material, may be critical. A world-wide survey, presented in Table 1.1, found that precast concrete is a universal building material, but mixed construction is limited mostly to developed countries where structural steelwork and types of timber, such as glue-laminated timber, is readily available. In addition there may be design, detailing, production, transportation, erection and maintenance limitations, which do or do not favour mixed construction.

1.2 Benefits

Mixed construction is now being used in more than 50 per cent of new multi-storey buildings in the western world. The increased use of precast concrete over the past ten to twenty years is due largely to the move towards greater offsite prefabrication of structural and non-structural components, and the sound economics, quality and reliability of doing so. However, some of the limitations found in precast concrete inevitably lead to it being used with other materials in a cost effective manner, e.g. to provide structural continuity and/or robustness using small quantities of cast insitu reinforced concrete (rc), or to form long span steel or timber roofs.

Structurally, combinations may work together or independently, but together they can be preferable to single material. The three examples seen later in this chapter [Figs 1-6 to 1-8] show that mixed construction was essential to meet the architectural requirements and the speed of construction, both of which translated into substantial savings overall. These are the primary advantages in using mixed precast construction.

One of the most common combinations is of precast concrete with cast in-situ concrete. The speed and quality of precast combine with the economy and robustness of in-situ to give high quality, aesthetically pleasing structures quickly and economically. This is especially true in seismic countries where the means of connecting precast elements is to form monolithic branches of reinforced concrete, which shift the failure zone away from the column and connection.

In some countries, such construction is called *'hybrid concrete construction'* (*hybrid* meaning the same material from two different parents). Structurally, these elements may be made to act together (compositely) or independently (non-compositely). It is sometimes difficult to say when an element or structure is composite or not, so boundaries are vague. The two parent materials may not even have any physical contact with one another but their use in one structure provides the benefits of both materials to specific projects. The benefits may not just be in the structural sense; advantage can be gained by combining architectural and structural functions, and structural and building services functions.

Another example is of structural steelwork and precast concrete. Their respective industries, which once competed with each other in the construction market, have now joined forces to provide the industry with new dimensions, seeking synergy in respect to their individual and mutual strengths or weaknesses. Designers of steel structures have found economy in using long span prestressed concrete floors, having a span-to-depth ratio of up to 50 and spans of up to 20 m, rather than being limited to short span metal decking.

The emergence of structural timber, particularly glue laminated timber, has provided new economic options for long span construction. When combined with precast concrete, timber provides good aesthetic and structural solutions as well as using local resources of timber and concrete. Innovative designs are emerging especially at the connections which are, by nature, visible in the final structure. The architect is allowing the structural engineer the freedom to express complex structural details.

Precast concrete flooring has had a long association with structural masonry, particularly in low rise housing. However, it is only recently that the two industries have formed alliances and provided technical design data, especially at bearings. Precast flooring now dominates the market share in load-bearing masonry buildings.

Although this new information, on both timber and masonry has encouraged the preparation of this document, caution must be exercised. The integration of two or more different building materials can cause procurement, detailing and manufacturing difficulties and greater design costs. The management aspects of 'just-in-time' deliveries from numerous suppliers must be considered. Changes to the way in which capital outlay is financed may be completely new and different to some engineers such that re-education is necessary in order to be successful.

A good example is where precast facades are used on a precast frame versus a steel frame – the implicit technology in the precast industry leads to a more streamlined design and hence lower costs. The whole concept of mixed construction is not only in matching a material's favourable properties, e.g.

concrete = compression and aesthetics,
steel = flexure,
timber = lightweight and aesthetics,
masonry = compression and geometric flexibility,

but also in ensuring that their boundaries are efficient and cost effective.

Major savings that accrue from rapid construction, timing of deliveries to site, reduced site labour and lower risks far outweigh additional costs of materials or design effort. Although the direct cost of a structural frame is probably less than 10 per cent of the total building works, the choice of materials and the indirect savings made in such areas as reduced area of cladding, reduced ceiling heights, lightweight components, reduced craneage costs, and stabilising methods, can be substantial.

1.3 Construction benefits

Mixed precast construction has many advantages over a single material, not least in on-site construction time where substantial time savings may be obtained. In some cases lengthy manufacturing lead-in times may reduce this advantage particularly in times of economic growth, although, by the definition of why mixed construction is specified at all, it should never overturn the advantage of mixed construction.

Compared to cast insitu concrete seasonal variations are less critical to site progress, and are totally nullified in the protective environment of the precast factory. Compared to in-situ concrete construction precast construction and mixed construction is safer and requires:

- less scaffolding, shuttering and formwork,
- less wet concrete and loose reinforcement on site,
- less site labour,
- less work for following trades, depending on integrated services,
- fewer bad weather delays,
- less time to complete the superstructure.

The use of structural steel frames with insitu floors, often supported on profiled metal decking of between 3 and 7 m span, is less efficient in comparison. Compared to using structural steelwork alone, mixed precast construction may require greater crane capacity, but otherwise requires:

- fewer elements,
- less fire protection,
- less wet concrete and loose reinforcement on site,
- marginally less site labour,
- less work for following trades, depending on integrated services,
- fewer bad weather delays,
- reduced construction time (but not as much as with cast insitu concrete).

1.4 Background: changing attitudes

Today, precast concrete is most commonly mixed with (in order of occurrence) structural steelwork, cast insitu concrete, masonry and timber. This form of construction has become increasingly popular in the past 10 to 15 years. The reasons may be traced back to changing attitudes in building design, especially since about 1980.

It is well known that precast concrete offers designers the widest possible choice in building construction, covering the full range of industrial, commercial and domestic buildings. Precasting concrete utilises the full technological spectrum in engineering design and properties of materials - the degree of innovation is limited only by the imagination of the architect, engineer and contractor, and budgetary constraints of the client. Most designers appreciate the major benefits in using precast concrete, such as high quality finish, fast erection, low maintenance, etc. In some countries the output capacity of the precast manufacturer, transportation and craneage are limiting factors.

However, back in the 1960's precast concrete was exploited by over-zealous clients and fabricators for use in modularised developments, where the architectural and engineering limitations of the material were cruelly exposed in the race to satisfy demand. This *production-orientated* design led to some oppressive architecture most evident in Eastern Europe.

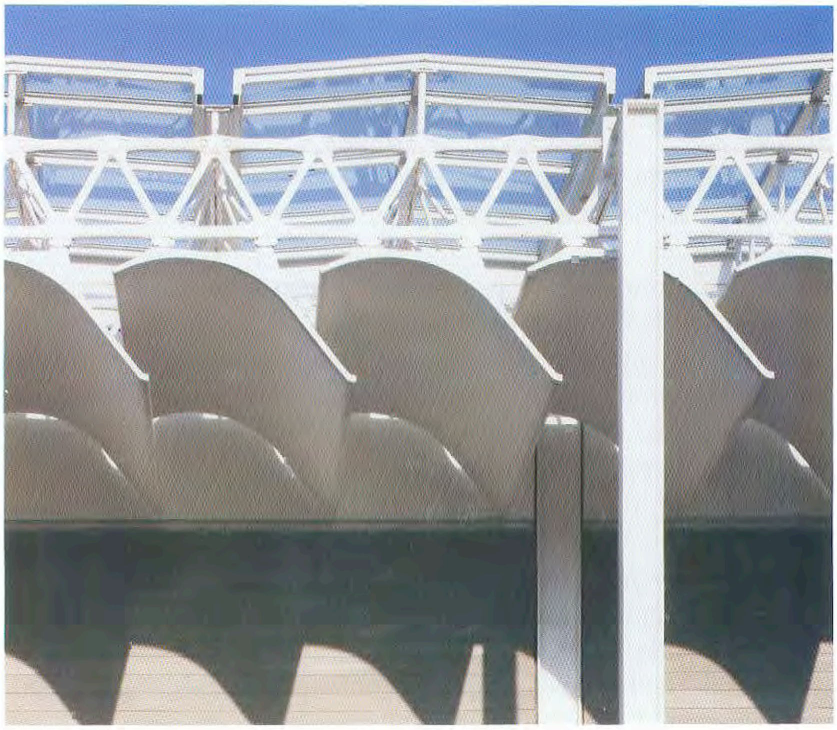


Fig. 1-4: Ferro cement roof structures, working in combination with tubular steel lattices, act as daylight reflectors to a Houston art gallery. (Courtesy of Ove Arup, UK)

As clients were able to become more discerning, they led a movement towards *design-oriented* building design that virtually eliminated precast concrete as the sole panacea for all construction. Today, designers utilise more than just the structural function of a building frame element. For instance, in the Houston Art Gallery [Barker *et al.*, 1983], shown in fig. 1-4, scalloped precast *ferro-cement* roof beams suspended of wrought iron trusses provide the means for reflecting natural daylight into the gallery below. Designers also utilise building materials to form a common function or effect, e.g. fig. 1-5, where white cement precast columns form the visual envelope and the structural frame. With this integrated approach to the design of the total building, prefabricators are now obliged to seek alternative ways in which precast concrete can be used to its full advantage.

This change in attitude coincided with a new movement in research and development. Scientists were beginning to exploit the benefits of composite construction, not only in the intrinsic interaction between structural steelwork and cast insitu concrete for example, but also in the manner in which different parts of a building interacted with one another for the mutual benefit of both.

Structurally, there was clear evidence that, provided on-site quality control was not compromised and the complexity of the construction required to achieve composite action was no greater than that normally employed, a more economical and integral structure would result. Bridge engineers had been using composite design for many years and researchers were able to determine design rules for both serviceability and ultimate load cases for buildings. Inevitably there arose problems of definition between composites and others which lead to the holistic notion of:

Fig. 1-5: Architectural / structural precast columns in white concrete support steel roof lattices. (Courtesy of British Cement Association, UK)

'composite construction' - the combined structural behaviour of individual components, e.g. composite floors;

'mixed construction' - the use of different materials and design approaches so that the whole is greater than the sum of its parts, e.g. precast concrete façade used to stabilise a structural steel frame.

Responding to the reduced market of the 1990's the industry saw a new movement in the design of mixed precast concrete buildings, and a new definition to the word 'design'. A big motivator was the push towards longer spans and reduced structural depths. In a shrinking market the design of structural concrete frames for prestigious commercial buildings came under closer scrutiny as architects, designer engineers and contractors strive to find optimum economy, speed of erection and the highest specification for their projects. The construction industry required a multiple choice in the selection of building components, and it was likely that the increasing demand on the performance of these components would overtake the existing technology used in their manufacture and utilisation.

Building design therefore became a multi-functional process where the optimum uses of all the components forming the building were maximised. Attention was directed towards the structural frame, which could no longer be considered as serving a structural function alone, but had to be harmonised with the requirements of the building in total. Architectural - structural precast concrete components were used on an increasing number of prestigious commercial buildings as specifiers became more aware of the high quality finishes possible in prefabricated units. But changes had to be made to the way in which traditional precast concrete structures were conceived and designed. In spite of the cut backs in staffing levels the precast concrete industry was ideally placed to accommodate these higher demands by using experienced design teams and skilled labour in a quality controlled environment to produce high specification components, which served the structural, architectural and services functions simultaneously.

1.5 Case studies in mixed construction

1.5.1 Example 1: steelwork, timber and masonry in a 7 storey precast frame

Precast concrete had a central role in the redevelopment of a confined city centre retail site in the UK, shown in figure 1-6. In order to increase off site prefabrication as much as possible, reduce the weight of the building components, and allow the maximum clear head height in the critical service routes, a mix of precast concrete, structural steelwork, timber and masonry (both brick and blockwork) was used in the super structure.

The foundations and other ground level work were cast insitu concrete. A cast insitu frame could not achieve the large floor spans and was found to extend the construction period by around 25 per cent, or 3 months. The structural engineer claimed that using different materials was the only way in which the site and building restrictions could overcome the architectural requirements – even though the geometric layout and structural design were quite simple.

Long span floors, typically 15 m length, of prestressed precast hollow cored slabs were supported either on prestressed concrete beams or on the bottom flanges of steel beams, depending on the allowable floor zone; the latter making a saving of around 250 mm per floor level to the headroom. Some of the precast concrete beam-column connections were made moment resisting using stiffened steel gussets (as shown in fig. 3-22 later). The staircases were also in precast concrete. Pitched timber trusses were supported by small section steel Universal beams - the small load on these beams precluded economic use of concrete beams.

Fig. 1-6. Mixed construction using different building materials was used – cast insitu and precast concrete, steelwork, timber, masonry. Offices and Car Park , Nottingham, UK.

1.5.2 Example 2: precast beams and slabs stabilised by tubular steel cross bracing

The VNO/NCW office tower in The Hague, Netherlands [Vambersky, 1996], shown in figure 1-7 was first conceived in wholly cast insitu concrete or steelwork. However in order to satisfy both structural and architectural demands, coupled with a need for a rapid construction programme, the designers chose to mix precast concrete beams and slabs with cast insitu columns and structural tubular steel bracing, figure 1-8.

Spanning 32 m over an existing highway this 13 storey building is in fact a series of strut-and-tie stability Warren trusses - ideal for high strength (grade B 85-95) precast concrete struts and steel ties. The floors are also of mixed construction using rapidly erected prestressed precast concrete hollow core units with an insitu topping to form horizontal wind diaphragms.

The load bearing interior structure is carried on a massive composite concrete truss; comprising a 2 m deep progressively post tensioned precast concrete lower chord and cast insitu diagonal and top chords. The designers claimed that, at that particular period in time and with the various constraints of geometry, site access, loads, etc. mixed construction was found to offer the best solution. [Vambersky web page].

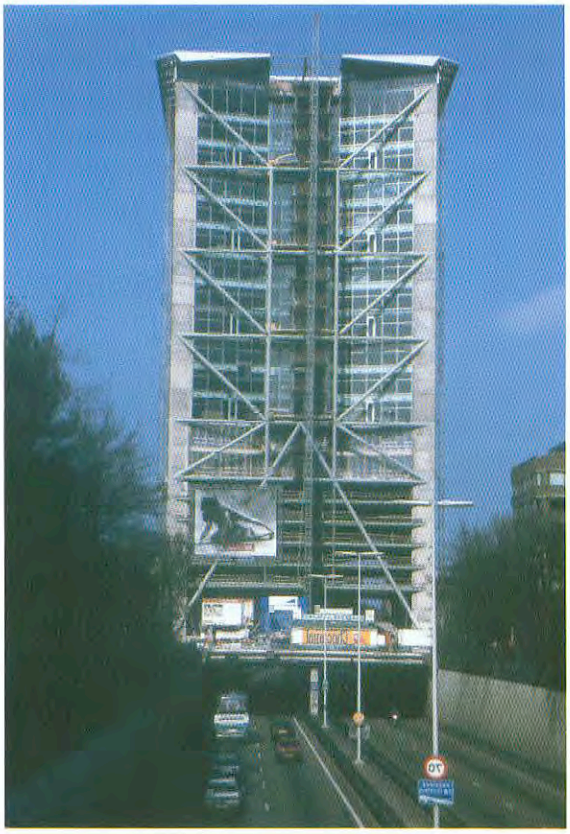


Fig. 1-7: Precast concrete, cast insitu concrete and steelwork in the VNO Building, Netherlands. (Courtesy of Corsmit Consulting Engineers, Netherlands)

Fig. 1-8: Interior view at VNO showing tubular steel bracing and precast concrete floors (now screeded finish). (Courtesy of Corsmit Consulting Engineers, Netherlands)

1.5.3 Example 3: precast floors and steel roof on prefab brick masonry pillars

A completely different example at the UK's Inland Revenue's headquarters used mixed construction to create both the façade and the load bearing structure, as shown in figure 1-9 [Evans, 1993].

Stabilised by cast insitu cores, prefabricated brickwork pillars supported precast concrete floors and steel roof trusses. Steel framed and glass clad ventilation towers were sited at the ends of the many notionally identical buildings to provide the means for natural ventilation. The 40,000 m^2 main load bearing structure comprised cast insitu concrete groundwork, prefabricated brick piers supporting precast concrete buttress blocks to carry 13.6 m long x 3.2 m wide floor units, expressed as a rippling concrete band of vaulted units at each floor level. The precast concrete components were manufactured in a single piece with dummy joints to give the appearance of number of individual arched units.

The alternative design would have been to support vaulted panel units on longitudinal beams spanning between the piers, interrupting the vista of open plan office space. This example shows how only mixed construction could have been used to satisfy both the architectural and structural requirements, and achieve the speed of construction.

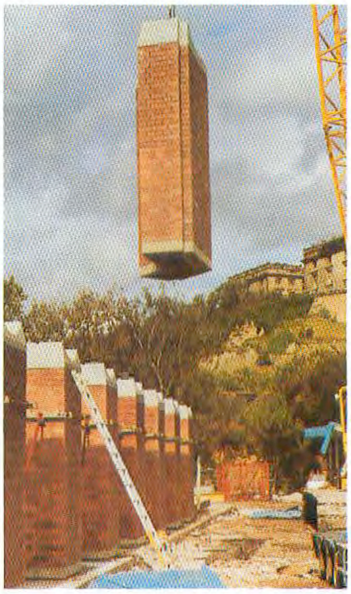


Fig. 1-9: Inland Revenue Building in Nottingham, UK. (Courtesy of Trent Concrete Ltd., UK)

1.5.4 Examples 4 to 6: precast stabilising and floor systems in steel frames

In many projects it is difficult to decide which material is dominant and which is playing the supporting role. In the office building that was shown in figure 1-2 slender hollow section steel columns and steel beams support prestressed precast concrete hollow core floor slabs. The slabs are recessed into the steel beams enabling spans of about 8 m to have an overall depth, inclusive of beam, of about 400 mm. The columns are braced using precast walls in two orthogonal directions. It is clear that neither the steel nor precast has the dominant role in this case. It is questionable whether the building in figure 1 -10 is a steel building with cast *insitu* concrete floors and precast walls, or a concrete one with steel columns?

Fig. 1-10: Steel columns in a concrete lift slab braced by precast walls.

The Scandinavian building in figure 1-11 shows how precast concrete, steelwork and timber can feature in the external façade, without necessarily being 'composite' in the structural sense. The South African building in figure 1-12 has load bearing masonry and precast concrete columns supporting steel beams and prestressed concrete floors.

Fig. 1-11: Precast concrete, steel, timber and glazing all feature in this building in Helsinki, Finland.

1.6 Comparison of construction methods

It is instructive to consider one of the most influential parameters in multi-storey buildings, that is the minimisation of the structural floor zone. Figure 1-13 shows a comparison of floor area (beam x floor span) with total structural depth achieved using the following mono and mixed cross-sections shown in figure 1-14:

1) cast insitu drop beams and slab,
2) structural steelwork and metal decking with cast insitu concrete topping,

Fig. 1-12: Precast columns, steel beams and masonry walls support prestressed concrete hollow core slabs. (Courtesy of Cement Manufacturers Association of Southern Africa)

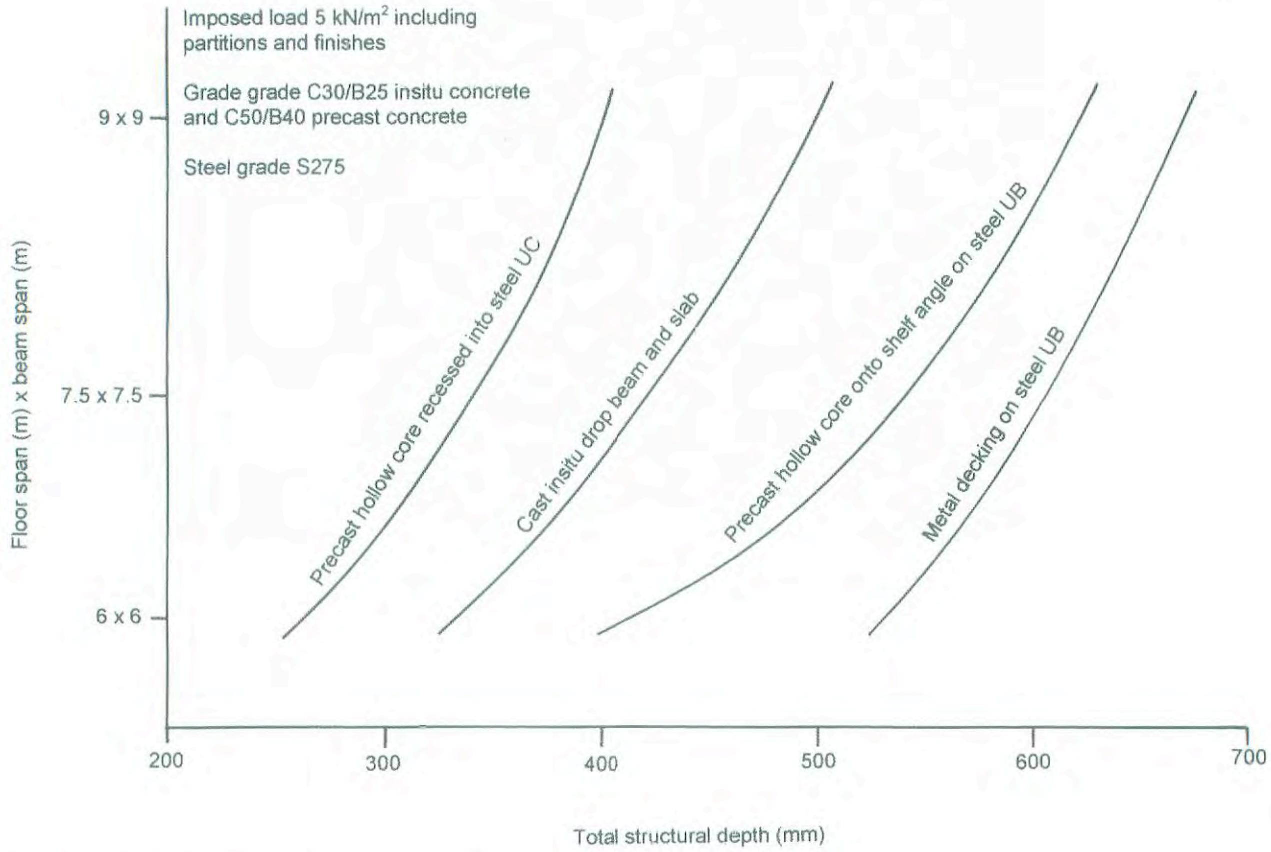


Fig. 1-13: Floor span x beam span data with respect to structural depth.

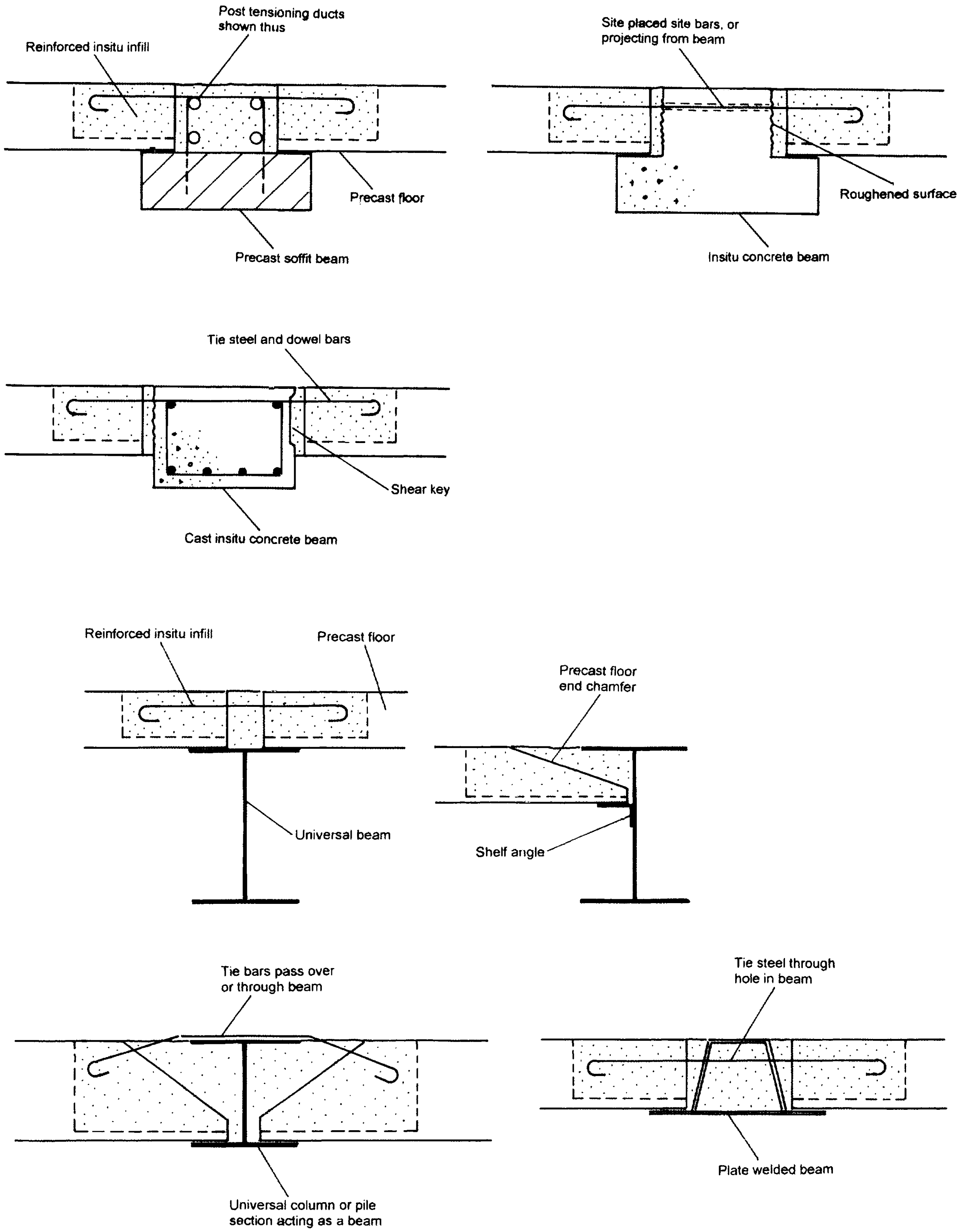


Fig. 1-14: Mixed construction for beams and floor slabs.

3) precast prestressed concrete floor units supported on:
   (i) the bottom flange of rolled Universal column (H section),
   (ii) shelf angle within a steel Universal beam (UB).

The data show that the deepest section is where metal decking sits on top of steel beams, being approximately 250 mm deeper than section type 3(i). For comparable loads and spans a saving of around 100 mm in depth is achieved using mixed construction floors, e.g. where the prestressed precast floors are supported on the bottom flanges of the supporting steel beam.

These formats might be seen as being more expensive than conventional arrangements but they lead to savings elsewhere. For example, if a commonly achieved floor-to-perimeter ratio of 0.2 is used with a cladding costing, say, US\$600/m^2, a reduction in structural depth of 150 mm may lead to savings equating to US\$10 to \$15/m^2 of total construction costs.

Further savings can be made if mechanical & electrical services are contained in the structural floor. Thinner floor zones may allow more storeys and/or make projects economically feasible within a specified planning height restriction.

1.7 Realising the potential

Mixed construction should, by definition, yield best value solutions. The greatest benefit from mixed construction is at the concept stage where possibilities are many and the cost-of-change is minimal, figure 1-15. At the detailed design stage, a large number of options remain available but by now the cost-of-change increases rapidly. The designer who conceives the building must be comfortable with all the viable options. The process of choosing between the options should be part of a 'value engineering ' exercise, where the entire design, construction and client team should examine whole life costs.

Figure 1-16 shows a schematic representation of the so-called *scope for project potential* where the number of possible options decreases as constraints become known and their number increase during the gestation of a project. Unfortunately the conceptual design is often carried out in the absence of the precast fabricator and it may be necessary to adjust the structural form when the means of achieving maximum potential with the precast structure is realised. Fabricators are always willing to contribute to initial designs. By using in-house expert knowledge, they can help reduce the construction time and costs and assure high quality – this is represented by point A in figure 1-16.

Although the number of constraints during the construction stage may be greater when using mixed construction compared with, say, wholly cast insitu concrete, the greater number and variety of options offers the contractor greater scope – point B in figure 1-16. The increased options are:

- alternative erection sequences, enabling *just-in-time* erection to proceed;
- earlier access to following trades, thanks to an absence of props and long maturity periods;
- better utilisation of plant, with cranes operating longer at optimum capacity;
- integral facades, where services are built in;
- more predictability and less risk caused by site delays;
- partial handover of building(s) to client, leading to earlier return of capital.

1.7.1 Local influences

Different forms of mixed construction may be popular in different localities because of the availability of local materials or the design know-how, see Table 1.1. Local circumstances also make comparison of costs fraught with difficulties as local economics, skills, climate, availability of materials and attitudes will dictate the outcome. It is however possible to state that whatever the local economy, mixed construction should be more cost effective than mono construction because a single material cannot possibly function in its most economical man-

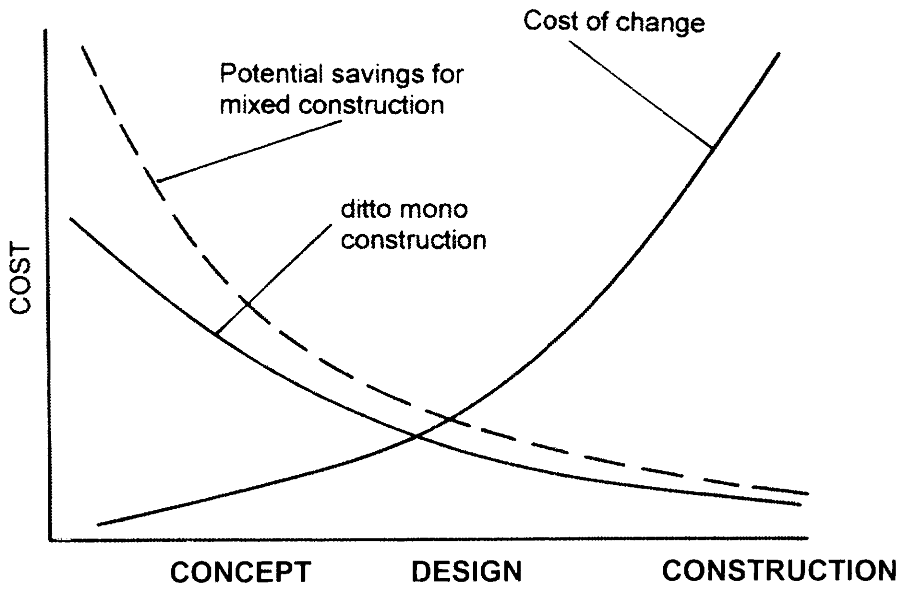


Fig. 1-15: Potential savings and costs versus time.

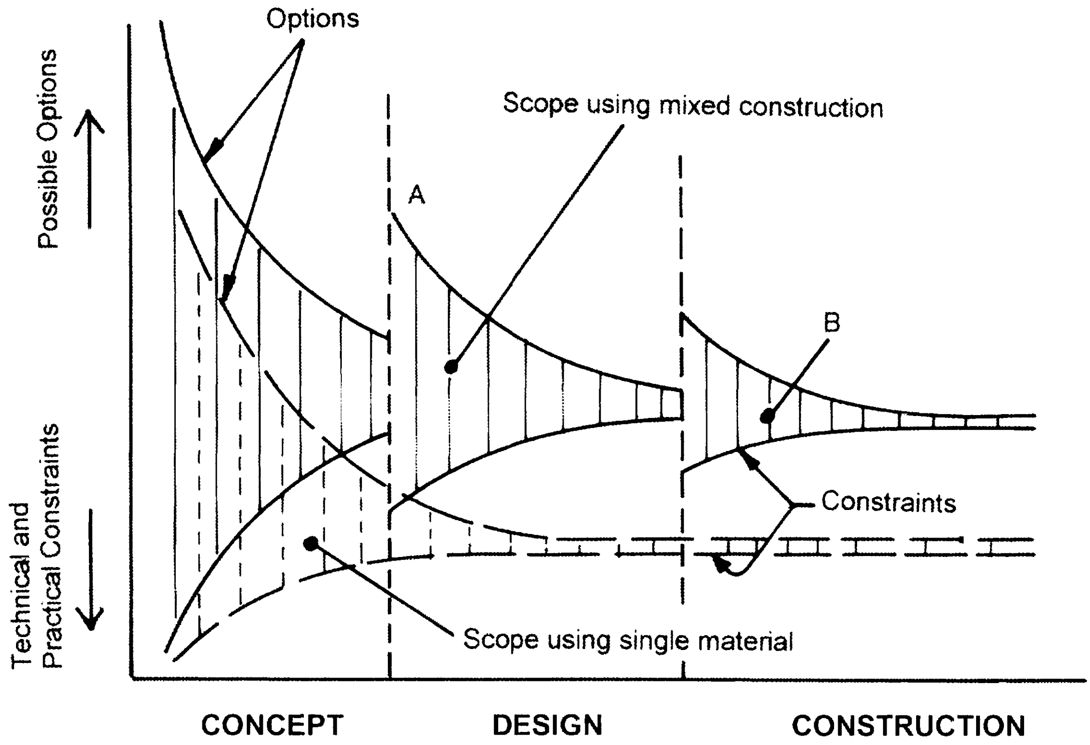


Fig. 1-16: Project scope defined by considering the options and restraints.

-ner in all situations. Worldwide, the combination of materials varies widely in mixed construction, but often reflects those used in mono construction as shown in Table 1-1.

Region	Mono Construction	Mixed Construction	Domestic	Comm-ercial & Retail	No. of storeys	Percentage of market	Precast share in a project
Northern Europe	CC, S, PC, M	S+PC CC+PC M+PC PC+S PC+CC PC+M PC+T	No No Yes No No No Yes	Yes Yes Yes Yes Yes Yes Yes	>2 >2 2-5 1-20 2-20 2-10 1-10	High Medium High Medium Low Low Low	Medium Low Medium High High High High
Southern Europe	PC, CC, M, S, T	CC+PC M+PC S+PC PC+CC PC+T	Yes Yes No No No	Yes No Yes Yes Yes	2-10 2-5 2-10 2-10 <5	High Low Low Medium Low	Low Medium Low High High
Scandinavia, including Finland	PC, T, CC, M, S,	S+PC CC+PC PC+S PC+CC PC+M PC+T	No Yes No Yes No Yes	Yes Yes Yes Yes Yes Yes	2-5 >2 1-20 2-20 2-3 2-5	Medium Medium High Medium Low Low	High Low High High High High
Middle East	CC	CC+PC S+PC M+PC	Yes No Yes	Yes Yes No	2-20 2-40 2-5	High Low Low	High Medium Medium
Russia (& former USSR)	PC, CC	CC+PC PC+CC	Yes Yes	Yes Yes	2-20 2-20	Low High	High High
Far East	CC, PC	CC+PC PC+CC	Yes Yes	Yes Yes	2-20 2-10	Low Low	Low Medium
China	CC, S, PC, M	S+PC CC+PC M+PC PC+S	No Yes Yes No	Yes Yes No Yes	<3 <5 2-3 1-5	Medium Low High Low	Medium Medium Medium High
Japan	PC, CC, S,	CC+PC S+PC	Yes Yes	Yes Yes	2-10 2-5	Low Low	Low Low
Australasia	CC, S, PC	CC+PC S+PC M+PC PC+CC	No No Yes Yes	Yes Yes Yes Yes	2-20 2-20 <5 2-12	Varies in different areas	Low Medium Medium High
North America	CC, PC, S, M, T	CC+PC S+PC M+PC PC+CC PC+S PC+M PC+T	Yes Yes Yes Yes Yes Yes Yes	Yes Yes No Yes Yes Yes No	2-40 2-15 <7 2-30 1-10 2-20 2-4	Varies widely in different areas	Medium Low Low Low Low Medium Low
South America (for Brazil only)	CC, PC	CC+PC PC+CC	No Yes	Yes Yes	2-10 2-20	Low High	Medium Medium
Southern Africa	CC, S, PC, M	CC+PC S+PC M+PC	No No Yes	Yes Yes Yes	>2 2-4 2-4	Low Low Low	Low Low Medium

KEY. CC = cast insitu concrete, PC = precast concrete, S = structural steelwork, T = timber, M = masonry

Table 1-1. Mixed Precast Construction Worldwide

1.8 Influence of building type on mixed construction

Mixed construction methods vary considerably with the type of construction and building function. These reflect local trends, environmental and physical conditions, relative material and labour costs, and local expertise. Although the permutations for mixed construction are numerous, Table 1-2 is a guide to their most common forms and combinations.

1.9 Influence of construction on design

As the complexity and number of different materials and joining methods increases, on site construction methods have an increasing significance on design details. Most of these concern connection details, jointing materials, and temporary stability.

In many instances the construction programme can dictate the design of the frame. The construction sequence and the type and capacity of the lifting equipment can determine positions and sizes of precast shear cores, walls and beams, glue laminated timber rafters etc. In the case of precast beams, limitations of size and handling weight can determine maximum spans - this is often not understood by designers accustomed to cast insitu or wholly steel structures where it is left to others to make these decisions.

The main decision to be made at the design stage is a logistical one. Construction sequences may be self-defined; with columns, cores, walls, beams, slabs and staircases being the obvious progression.

Building type	Mixed precast construction methods	Comments
Commercial offices	Insitu concrete frame with precast flooring and facades. Steelwork frame with precast shear walls, flooring and facades. Precast frame with steel raker ('Mansard' type) or steel roof truss. Precast frame with pitched timber truss.	All combinations possible with insitu concrete under-ground or ground floor podium.
Retail and shopping	Insitu concrete or steel frame with precast flooring and facades. Precast load bearing wall with cast insitu floors. Masonry load bearing walls with precast floors.	Ditto
Educational buildings	Steel frame with precast floor, with steel or timber roof Load bearing masonry with precast floors	Maximum clear spans to allow for changes in use
Parking Garages	Insitu concrete or steelwork frame with precast flooring and cast insitu topping Precast frame with glue laminated timber or steel roof	Long span double tee floors up to 20 m
Industrial and warehouses	Steel frame with long span precast wall units. Precast columns with steel roof truss. Steel frame with precast floors (office areas).	Hollow cored or sandwich walls give thermal insulation. Long span lightweight roof.
High rise residential	Precast load bearing walls with cast insitu floors. Masonry load bearing walls with precast floors.	Composite floor plank often used because of complex floor plan layout.
Domestic, low-medium density	Masonry load bearing walls with precast floors. Precast walls with timber floors.	Beam-and-block precast and hollow core dominates.
Stadia	Steel frame including raker beams, with precast terraces. Cast insitu frames with precast terraces. Precast columns with steel raker beams and precast terraces.	All combinations possible with steel or pretensioned precast roof.

Table 1-2. Building Types Using Mixed Precast Construction

In a situation where either precast or mixed construction is chosen the following points should be considered:

1. Positions of stability cores, walls, bracing etc. In high rise buildings the most popular method is a cast insitu core constructed several storeys ahead of the framework. In medium height buildings this may be precast concrete or brick infill, steel cross bracing or precast concrete diagonal bracing.
2. Maturity of connections (which may dictate or alter planned site progress unless it is properly managed). Cast insitu grouted joints need a few days of temporary propping unless combined mechanical connections are also used.
3. As a consequence of item 2, the need to design some of the key components to achieve temporary stability;
4. The availability and/or positioning of equipment to transport and erect components. The size and weight of the various components should be organised to make optimum use of crane capacity, e.g. the lightest units furthest from the operating zone.
5. Erection safety and speed of construction, with attention to cast insitu concreting sequences. This is particularly important where fixing gangs are unaccustomed to working with different materials, especially steel fixers asked to erect precast concrete.
6. Tolerances for economical construction, particularly where different manufacturers are producing components in different materials. Item 5 also applies here.

1.10 Summary of chapter 1

Mixed construction is today being used in more than 50 per cent of new multi-storey buildings in the western world. This was once the traditional domain of cast insitu and structural steelwork. A similar story exists with single-storey industrial buildings, once the domain of long span prestressed concrete. Precast concrete is taking a part of nearly every new building in most areas of the world – the contribution varies from around 10 per cent where cast insitu dominates to 90 per cent where precast dominates. It is taking this share as it provides better value in increasingly competitive markets.

Mixed construction is a technologically advanced approach to frame construction - it requires the co-operation of architects, consulting engineers, manufactures, suppliers and contractors. It is being exploited to great advantage of buildings of 3 to 15 storeys generally, but up to 50 storeys in isolated examples. It is possible that some client and architectural demands can **only** be satisfied using mixed construction.

2 Precast concrete with cast *insitu* concrete

2.1 Introduction

Perhaps the biggest misconception associated with adding *insitu* concrete to precast concrete is one of terminology. Where the design makes specific allowance for interaction of the two materials in order to increase the structural (or otherwise) capacity of either concrete, this is *composite action* and is therefore beyond the scope of this publication. Reference may be made to the recent FIP document on horizontal composite structures [FIP, 1998]. In *mixed construction insitu* concrete is inevitably and surely active with precast, but in the true sense of the definition the structural performance of the precast is not necessarily increased. There is a fine dividing line between the two!

Mixed construction with *insitu* concrete has been achieved in the following manner:

- precast floors, chiefly prestressed hollow core and double tee units, and/or soffit planks (composite planks) onto cast *insitu* beams, engaging composite action or not depending on project needs,
- supplementing precast beam elements for cast *insitu* beams in cast *insitu* frames,
- precast U or shell beams filled with reinforced or post tensioned cast *insitu* concrete,
- cast *insitu* toppings or non structural finishing screeds on precast floors,
- precast concrete façade panels on cast *insitu* concrete frames, exploiting the mouldability and texture of factory cast concrete.

In the true spirit of mixed precast-*insitu* construction precast concrete is used ostensibly as a 'permanent horizontal formwork', either for beams or slabs. Spandrel, L or U-shape troughs cast in thickness of 30 to 100 mm may provide not only the formwork but also the visual façade, for example in figure 2-1.

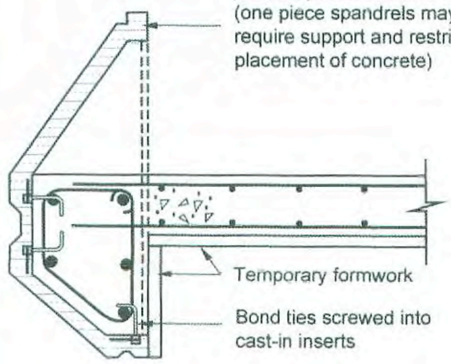


Fig. 2-1: Precast permanent shuttering for cast insitu concrete floors at City Corp Centre, Sao Paulo. (Courtesy of Mario Franco, Brazil, left, and Reinforced Concrete Council, UK, right)

Under certain climatic conditions this details makes a thermal bridge to the floor slab. Integral insulation would need to be provided to avoid this. For the outer skin, polypropylene or short steel fibres (at about 0.5 % by volume dosage) may be used to reinforce the thinnest sections, as little as 20 mm thickness is possible. This detail would also provide peripheral tie steel between the beam and floor slab, as well as the edge tie to columns. Generally the prestressed precast concrete is of strength grade (cube/cylinder N/mm^2) C 50-60 / B 40-50, the reinforced precast is C 40 / B 30, whilst the cast *insitu* is C 25-30 / B 20-25.

2.2 Precast concrete floors on cast *insitu* beams

In internal locations permanent precast soffit formwork (occasionally prestressed or post-tensioned) provides the support for precast concrete floors and cast *insitu* beams as shown in Figure 2.2. The projecting links for part of a 'warren' truss used to carry the self weight of the slab. Although there is some inevitable composite action between the precast soffit units and the *insitu* beam, the proportions are such that it is not significant, and certainly not an economic consideration. Typical dimensions for the permanent precast soffit formwork are 600 – 1000 mm wide and 80 - 120 mm deep. The *insitu* concrete must be confined in a transverse direction by site placed bars positioned into the precast floor units, as shown in figure 2-3.

In this project precast prestressed precast hollow core units, 300 mm deep x 1200 mm wide, were chosen. The same bars provide continuity of the hollow core unit in a hogging mode across the beam. (For design details see ref. 6.) The resulting span-to-depth ratio for this construction is around 20:1 for imposed loads of 5 kN/m^2, compared with about 15:1 if precast was used alone. The speed of construction is slower than for wholly precast because of wet casting, but the overall benefits in longer span beams and reduced numbers of columns and foundations outweigh this fact.

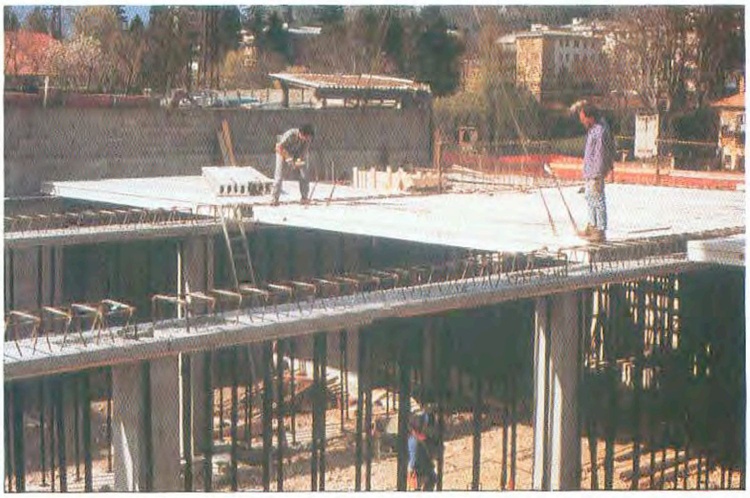


Fig. 2-2: Precast soffit formwork used as permanent shuttering for insitu beams and long span floors. Commercial building in Novara, Italy. (Courtesy of APE and Gruppo Centro Nord, Italy)

The width of the precast soffit formwork may be up to about 1250 mm, although the additional expense in propping units of such large width may be detrimental to the case. In the building shown in figure 2-4, these units span longitudinally between precast walls, where they in turn support transverse hollow core units. The span-depth ratio here is 25:1 for imposed loads of 5 kN/m^2.

We note a twenty-five per cent increase in span and in the effectiveness of this arrangement compared with that in figure 2-2, and a reduction in quantity of steel rebar of around 15 % compared with cast *insitu* flat slab, although much of the reinforcement used here was pretensioning strand which costs more than rebar.

Wider precast soffit units, acting as permanent formwork, may be used up to about 1.5 m wide, but as mentioned before the addition of extra lines of props to prevent overturning may be costly.

Fig. 2-3: Completion of precast – cast insitu floor. Offices, Turin, Italy. (Courtesy of Gruppo Centro Nord, Italy)

Fig. 2-4: Wide insitu concrete beams supporting precast concrete hollow core floors at an underground car park, Parma, Italy. (Courtesy of Gruppo Centro Nord, Italy)

The contribution of *insitu* concrete is increased further if post-tensioning is used (the beams must form straight continuous lineage to be effective). The tendons are placed either in the centre of trough, U-shape beams or to either side of inverted-tee beams as shown in figure 2-5. The post tensioning stress in the beam is typically 5 to 10 MPa. In these cases composite action is inevitable because the inter-faces are castellated to form shear keys. Care must be taken when post-tensioning beams of unequal spans or of unequal loads.

The U beam, called *beam shells*, has formed the basis of precast construction in many seismic zones where the cast *insitu* infill becomes the primary structural section. Designers in the US, New Zealand and Japan are keen on this. The prestressed (or reinforced) shell act as supports for floor units during construction. The *insitu* concrete core inside the shell acts compositely with the floor and topping, if present. The precast part may actually be discounted, particularly at the connection where the shell terminates at the face of a supporting wall or column, as shown in figure 2-6.

The precast shell is not connected by reinforcement to either the *insitu* infill or the column. The column is structurally continuous and the beam-to-column connection is flexurally rigid. Although the precast contributes about 30 - 40 percent of the concrete section the saving in

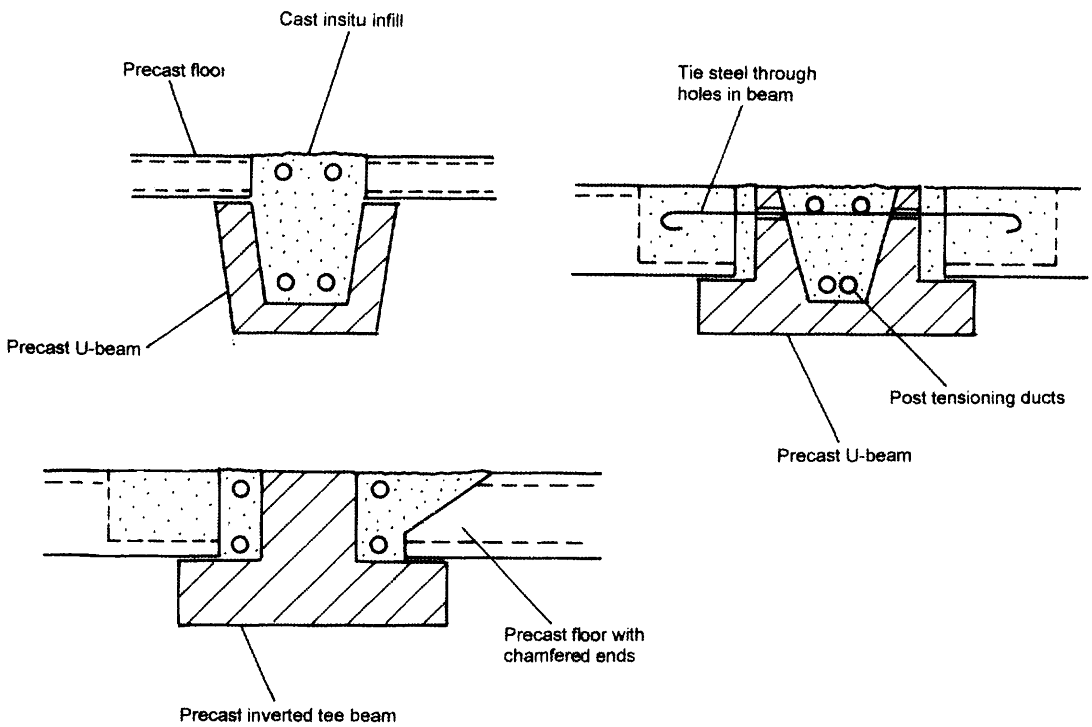


Fig. 2-5: Precast beams awaiting infill concrete and post-tensioning [top] in the trough of U-beams [bottom] to the side of inverted tee beams.

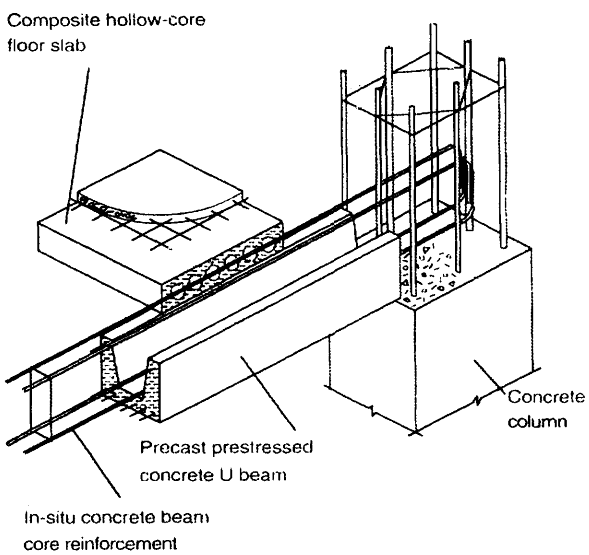


Fig. 2-6: Precast shell beams with cast insitu concrete cores. (Courtesy of Prestressed Concrete Institute, USA)

falsework is about twice the cost of the precast element. The span-depth ratio is not as great as in the cases shown in figures 2-2 and 2-4, but the solution provides a very efficient solution.

Precast floor units may be erected during the construction of cast *insitu* beams and columns. Figure 2-7 shows the simultaneous construction of precast and *insitu* work. However, it is not always necessary for this to happen together. Figure 2-8 shows where a precast floor is supported on the edges of an arched steel mould prior to cage fabrication and casting of a post tensioned beam. By casting reinforcing bars (typically 10-12 diameter at 300-600 mm spacing) into the slots in the floor units, composite action also takes place.

thereby increasing the flexural strength and stiffness of the beam. The advantage of this method is the bending stresses due to self weight are resisted by the fully composite beam, rather than by the beam alone. This can make a substantial difference to the cross sectional mass of the beam if the governing criterion is the serviceability limiting stress.

Fig. 2-7: Precast concrete hollow core floors with cast insitu beams and columns.

Fig. 2-8: Precast U-shape or shell beams awaiting post tensioning. (Courtesy of Concrete Society, UK)

Figures 2-9 and 2-10 show similar approaches in the Far East and South Africa of placing prestressed hollow core floor units on to timber formwork prior to casting *insitu* concrete beams or on to pre-site cast beams. Wet bedding on to 2-3 mm layer of mortar may be necessary where wide slabs, greater than about 600 mm wide, are laid directly onto cast *insitu* beams. Dry elastomeric or felt strips can be used.

The speed at which the precast floors are laid usually exceeds the speed at which the shuttering and casting of the concrete beam is carried out. Consider the example where the turn around time to construct *insitu* beams supporting about 100 m^2 of flooring per beam is around 3 days. If 5 to 6 beams can be constructed at the same time this yields sufficient support for around 500 m^2 of flooring, which (according to typical fixing rates) takes about 2 to 3 days to erect.

Fig. 2-9: Precast concrete hollow core floors supported on post-cast insitu beams.

Fig. 2-10: Precast concrete hollow core floor slabs supported on previously cast insitu beams (Courtesy of Concrete Manufacturers Association, South Africa)

Where a structural topping is used the number of beams required to keep pace with the flooring reduces by about 50 %. This method has been used in figure 2-7 where the pace of erecting the precast hollow core slabs was quicker than the casting of supporting cast *insitu* columns and beams.

The workforce to produce the *insitu* is about 6-8 times that employed to erect the precast version. The beams are continuous across the top of the columns, and the infill topping to the beams makes it behave compositely with floor slab.

These rules for concurrent progression do not always hold. In figure 2-11 the cast *insitu* work for an entire floor area, some 3000-4000 m^2 was completed before the precast terrace units were delivered. This is one of the stadiums for the 2004 European Soccer Championships, and included large areas of hollow core floor units in the reception and circulation areas beneath the terraces, Figure 2.12. To increase the continuity between the 15 m span slabs and the beam, milled slots, almost 1 m long were factory cut to receive site placed bars.

Modular formwork, together with pre-assembled reinforcement cages, may be designed to support the self weight of the precast slabs, as shown in Figure 2-11. The beams, which may be post tensioned as in this case, are cast compositely with the precast units to form a monolithic floor in grade C 40 (cube strength) concrete.

Fig. 2-11: Precast terracing units being placed onto cast insitu raker beams at Sporting Lisbon FC, Portugal, soccer ground.

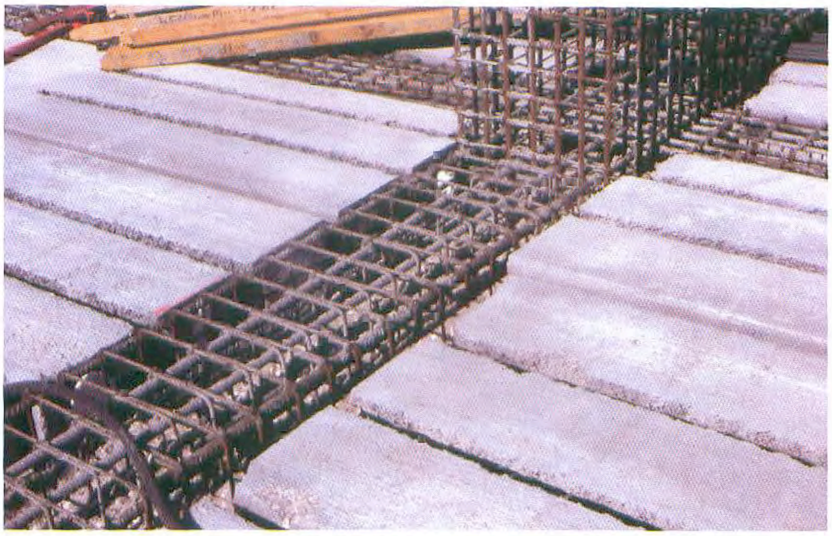


Fig. 2-12: Detail between the ends of prestressed hollow core units and an insitu framework at Sporting Lisbon FC.

Mixed precast-*insitu* concrete buildings of between 3 and 10 storeys are constructed in this way at the rate of up to 1500 sq. m per week using one fixing gang with one crane. This can only be achieved where more than 50 % of the concrete is produced off site and that the production of precast elements do not lie on the critical path.

One of the best examples of this is in the project shown in figures 2-14 where two identical frames comprising 116,000 m^2 floor area were constructed in 15 weeks [Charlesworth, *etal*, 1995]. They comprised:

- cast *insitu* lift shaft cores, columns and post tensioned beams,
- 66,000 m^2 precast concrete hollow cored floor units with a 75 mm polypropylene fibre reinforced structural topping,
- 100 no. precast concrete staircases,
- modular falsework and prefabricated rebar cages included the post tensioning sheaths.

Fig. 2-13: Precast hollow cored floors suspended between post tensioned cast insitu beams. (Courtesy Reinforced Concrete Council, UK)

Fig. 2-14: Precast and cast insitu concrete combined to construct 3000 parking spaces in 8 months. (Courtesy of Reinforced Concrete Council, UK)

The main technical issues concerning precast floors on cast *insitu* concrete beam and walls are:

- Bearing lengths: The nominal bearing length for prestressed floor units which have tendon reinforcement continuing to the ends of the units is about 75 mm. This assumes the cover to the reinforcement in the cast *insitu* beam is about 30 mm. Where reinforced floor slabs themselves have end cover to reinforcement of, say 30 mm, the nominal bearing length should be about 100 mm.
- Tolerances: Prestressed hollow core floors are manufactured to an accuracy of about ± 10 mm; in fact most producers will cut the units slightly longer than

shorter to avoid insufficient bearings. Cumulative tolerances, together with cast *insitu* inaccuracies, are about 25 mm.

- Continuity tie steel: Where a structural topping is not used, for example in hollow core floors, tie steel is placed either in broken out cores, typically 2 or 3 per 1.2 m wide unit, or is placed in the longitudinal gaps between units. A full anchorage bond length must be provided. Tie steel positioned perpendicular to the span of the floor is placed over the top of beams (or to the side of) and contained within loops projecting from the beam. Alternatively tie steel can be regarded as part of the main reinforcement in the beam, in which case no extra site placed bars are necessary.
- Shrinkage and other volumetric movement causing cracks at the precast-*insitu* joint, can also be associated with pre- and post-tensioning. This is normally controlled by tie steel crossing the precast-*insitu* interface. If cracking is to be mitigated even further, the concrete infill should use have a low free-water content or contain expansive cement, superplasticizer, etc.

2.3 Cast *insitu* toppings on precast floors

Cast *insitu* concrete is added to a wide range of precast concrete floors to form finishing screeds or structural toppings. A '*screed*' is defined as a finishing layer, often power floated smooth and level. However if the '*topping*' is serving a structural purpose it must be 'properly' bonded (according to codes and best practice guides) to the precast units and reinforced. The thickness of the topping should not be less than 40 mm at it thinnest part, 50 mm to 75 mm being typical. A structural mesh is continuous in the topping and is tied to perimeter beams, whatever their type, to form horizontal wind diaphragms. Figure 2-13.

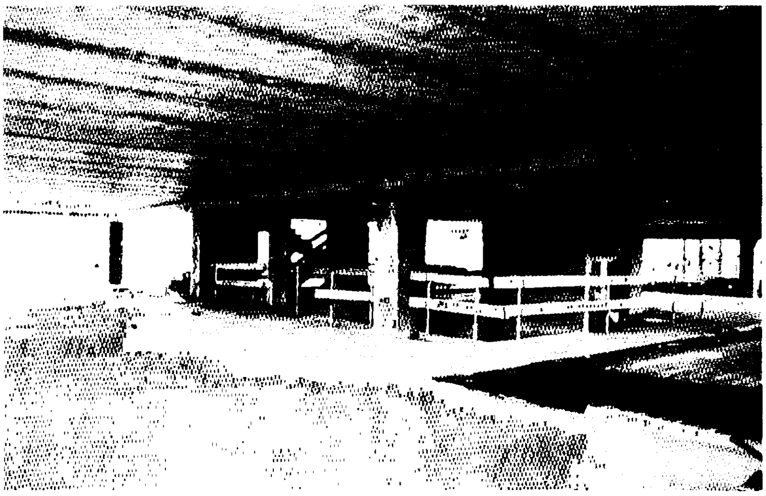


Fig. 2-15: Cast insitu structural toppings to precast concrete floor units.

Cover to the mesh should be 25 mm. This is particularly important at laps where up to three sheets of mesh overlap (nested mesh reduces the total depth of bars). Double-tee units with shallow flanges must have a topping of 50 to 70 mm thickness to ensure diaphragm action and to strengthen the flanges. In this way the precast unit is acting as a permanent shuttering with good flexural and shear capacities.

Toppings are added to hollow core units in some instances – for example where water tightness is required or delicate finishes (including screeds and plastered soffit) may be broken by cracks along the longitudinal joint between units. The hollow core units should be matured for a number of days depending on ambient humidity etc. to reduce on site shrinkage. Bonding agents are recommended for plastered ceilings. There is no structural reason for using a topping to hollow core units, except perhaps to increase the flexural capacity (by 10 - 20 % typically), or to increase the thermal, acoustic or dynamic behaviour. Toppings are essential to form horizontal diaphragms is seismic areas. The quantity of *insitu* concrete required is between 30 % (for 300 mm deep slabs) and 50 % (for 150 mm deep slabs) of the precast unit. The cost of a topping is about 30 % the cost of the precast unit – about US$8-15 per m^2.

2.4 Precast concrete frames on cast *insitu* concrete

It is common for cast *insitu* concrete to be used solely for the substructure (e.g. underground car park, access ramps, retaining walls and foundations) or even a ground floor podium where the layout or elevations might not be suitable for precast framing, both structurally and economically. The precast columns in figure 2-16 are bolted through base plates to the top corners of cast *insitu* retaining walls. The practical problem here is due to settlement of the *insitu* concrete wall leaving behind a 3-5 mm thick fatty laitance underneath the base plate, which should be scraped away. A levelling allowance of 30-40 mm should be provided for precast column foundations and 10-15 mm for beam bearings.

Fig. 2-16: Precast concrete columns bolted to cast insitu retaining walls.

Structural compatibility is not a problem provided that the boundaries between the cast *insitu* and precast elements are well detailed to prevent cracking and debonding – roughened surfaces, shear keys etc. Providing the differences in behaviour of a continuous rigid *insitu* frame and a pin-jointed precast structure can be accommodated in the stability analysis, the main problems are associated with the design of the joints.

Precast-to-*insitu* connections rely on accurate on-site work because the tolerances in precast work are much less than *insitu* work, e.g. 6-10 mm rather than 20-30 mm. Typical beam-to-column connections are shown in figure 2-17. *Insitu*-to-precast connections may be less tolerant towards accuracy as the *insitu* takes up inaccuracies. However the joint relies on adequate bond developing between the two concretes, which must be designed so that the precast element can resist the new set of forces resulting from the changes in detail. The effects of shrinkage must be considered particularly if the connection is of major structural importance, as in the case of a moment resisting joint.

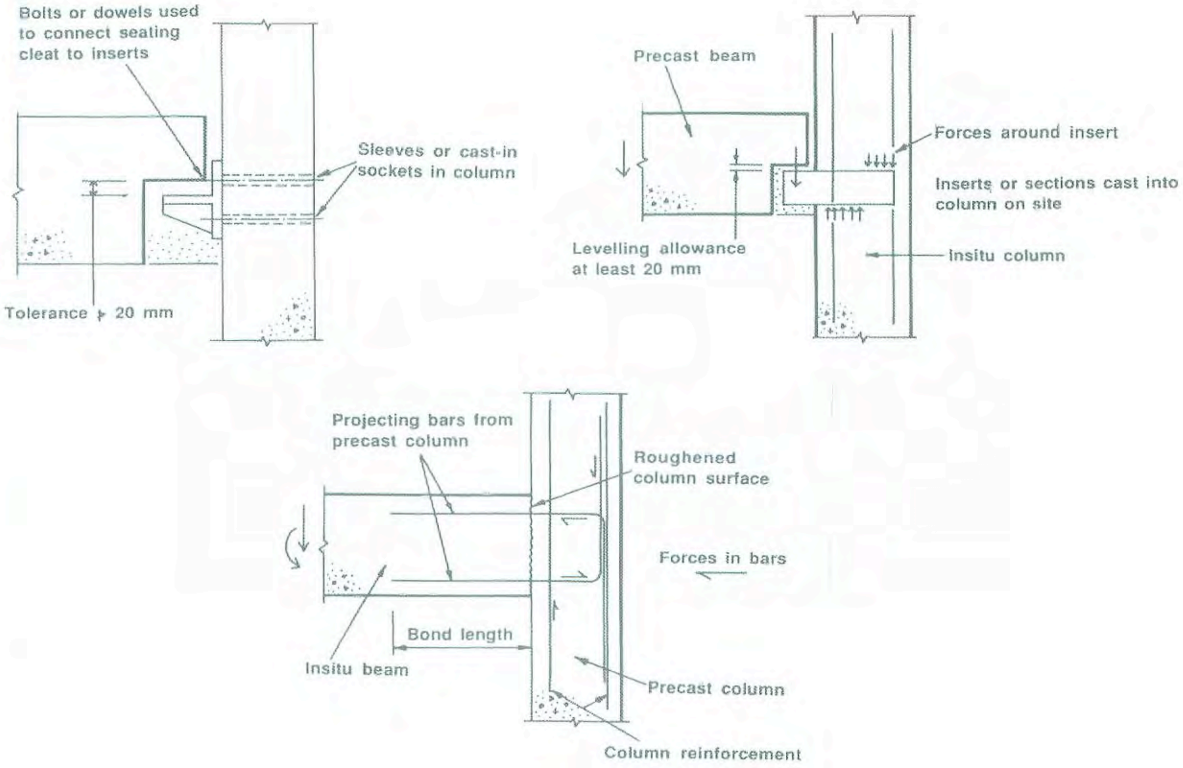


Fig. 2-17: Precast-to-insitu concrete connection details.

Fig. 2-18: Oval yokes in precast units form cast insitu connections with insitu concrete columns. (Courtesy of Trent Concrete Ltd., UK)

These concepts are illustrated in fig. 2-18 where precast concrete end yokes were cast to *insitu* columns through a circular hole. (A similar concept is seen later in figure 3-14.)

Further details of the construction technique at the VNO building (introduced in Chapter 1) are shown in figure 2-19. Temporary shoring up of precast concrete spandrel beams meant that the cages for cast *insitu* columns could be accurately positioned. The beam-to-column connection was made monolithic by concreting in rebars projecting from the precast beams.

The column was cast in one continuous pour using grade B 85 concrete up to the level at the top of the precast spandrel beam.

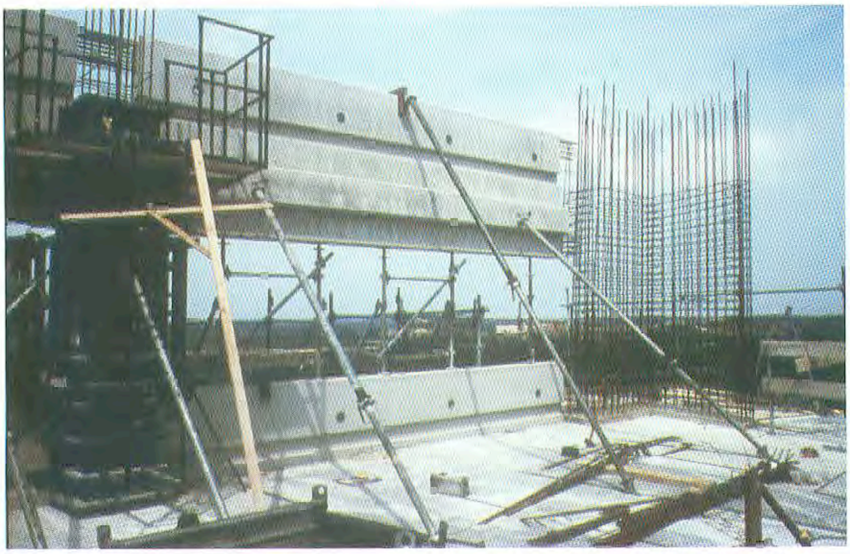


Fig. 2-19: Precast concrete spandrels attached to cast insitu columns at VNO Building, Netherlands. (Courtesy of Corsmit Consulting Engineers, Netherlands)

The main technical issues concerning precast frames on cast *insitu* concrete are:

- Settlement of *insitu* concrete in walls or columns. Laitance seen at the top of an *insitu* concrete pour may cause practical, rather than structural, problems at the bearing of precast columns or beams. The best remedy is to remove the fatty material down to sound concrete, building up as necessary with dry packed mortar.
- Steel levelling plates should be wet bedded onto *insitu* mortar (or grout). Elastomeric bearing pads are used in most cases (the exception being very short beams where end rotations are small).
- Tolerances at holding down bolts. Some 50 mm of lateral movement should be provided to holding down bolts in cast *insitu* foundations. This is achieved by 'cracking' the bond around the bolt when the *insitu* concrete is less than 24 hours old.
- Projecting rebars or dowels (often called 'waiting bars') to receive precast columns or beams are mostly of diameter < 25 mm. The minimum projection should be 300 mm or the depth of the beam minus 25 mm cover.
- Differential movement and shrinkage rates are allowed for in the analysis, normally taken as 100 x 10^{-6} strain. Differences in Young's modulus are ignored even though the strength of the concretes may differ.

2.5 Precast facades on cast *insitu* frames

Precast concrete façade units adorn many cast *insitu* frames, figures 2-20 to 2-22. This is also known as 'hybrid concrete construction'. The panels are, by nature, intentionally of large mass and require great stiffness in the supporting frame to avoid beam deflections causing misalignment in the fixings. The maximum number of fixings should be four, of which not more than two should be load bearing – the other two provide horizontal restraint either at the top or bottom of the panel.

The span-depth ratio for a concrete beam required to avoid differential deflections across the width of a panel of less than 5 mm should be 15 – 20 for panels of up to 2 m in width, and

10 – 15 for panels of 3 m width [Taylor *et al*, 1992]. When supporting large panels on flat slabs checks should be made that both short term and long term (creep etc.) slab deflections do not cause spurious displacement reactions in the fixings.

The effects of thermal movement should be allowed for particularly if the supporting frame will not be exposed to the same temperature fluctuations as the panels. The situation is more complex at corners where differential movement must be accommodated in two directions.

Fixing and joint tolerances at internal corners should be at least 5 mm greater than at plain joints to prevent closure forces inducing shear and bending in the panels and prying forces at the fixings. Cast in channels offer a good solution provided the edge distance is maintained at corners. Post drilled fixings, such as expanding bolts or resin capsules, can be made during construction. The tightening torque should be specified.

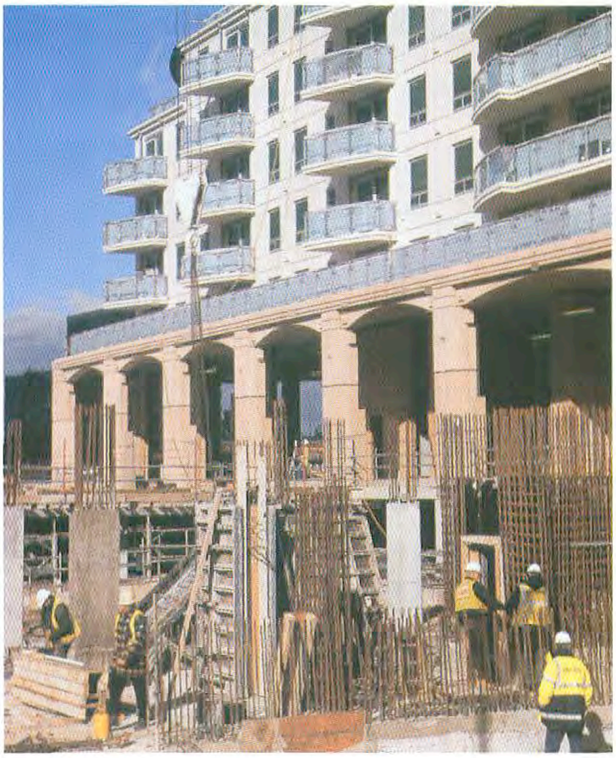


Fig. 2-20: Precast cladding on cast insitu frame - 750 apartments at St George Wharf, London. (Courtesy of Thomas Telford Ltd., London)

The main technical issues concerning precast façades on cast *insitu* concrete are:

- Standardised details. This industry is attempting to produce standard details to cover all situations, but this is an uphill task as the number and complexity of bespoke and innovative buildings continues to increase.
- Fixing tolerances. All fixings must be capable of three-dimensional adjustment including differential thermal and shrinkage effects. Typical tolerances of about 50 mm are achieved either by using oversized dowel holes or elongated slots in brackets.
- Small bearing areas close to free edges. It is quite common for the bearing dimension to be less than about 200 mm in size and around 75-100 mm from a free edge. This may cause large bearing pressures and lateral splitting stresses in concrete that is not reinforced at free edges or corners. This may be due to the radius of the bend of the corner bars. Alternative details are therefore required.
- Uneven bearings. These can be overcome by sufficient adjustment in the brackets.

Fig. 2-21: Reconstructed stone precast cladding on cast insitu frame at Vauxhall Cross, London.

Fig. 2-22: Shopping Centre, Perth, Australia. (Courtesy of National Precast Concrete Association of Australia)

2.6 Summary of chapter 2

Precast elements are combined with cast *insitu* concrete in a wide range of multi-storey buildings. This *hybrid* combination works best where long span prestressed precast concrete floors are connected to either precast or cast *insitu* beams using small quantities of reinforced or post-tensioned concrete.

Examples of construction projects given in this chapter have shown us *how* and *why* precast and *insitu* concrete can be combined to enhance both the architectural and structural aspects of design, improve buildability and make use of local resources. The examples have originated from all parts of the world.

The reasons *why* mixed construction was chosen for these projects varied widely, often involving the availability of local resources, materials, skills and design know-how. Although the major decisions whether to go for mixed construction or not would usually be at the behest of structural engineers, it is unlikely that the rationale behind the final decision would be based on structural engineering rationale alone.

3 Precast concrete mixed with structural steelwork

3.1 Introduction

Structural steelwork enjoys a very high profile in some countries, chiefly the UK, USA, Australia and Japan. Its success has been the result of concerted research and development, and flexibility of design, procurement and construction. Some of these factors have been denied to the precast concrete industry, such that steel has succeeded as a building material in its own right.

When mixed with precast concrete, steel's structural properties can be clearly beneficial (e.g. lightweight long span roofs, stocky beams with shallow bearing ledges) but other properties are not. Some of these properties, such as thermal, acoustic, maintenance, appearance and fire resistance, are becoming increasingly dominant in modern times. Substituting of a precast element with steel one must be carefully appraised.

Precast concrete is used mainly in conjunction with structural steelwork for:

- long span precast concrete floors supported on steel beams,
- precast beams supporting metal decking floors,
- precast walls used to brace steel frames,
- precast frames stabilised by steel cross bracing,
- precast columns supporting lightly loaded roofs, e.g. trusses or cantilevers,
- precast columns supporting steel roof frames, e.g. portals, mansards,
- precast facades on steel frames.

3.2 Precast floors in steel frames

Most engineers' vision of "mixed" prefabricated construction is precast concrete floors supported on steel beams, often taking advantage of composite action that can be achieved using a small number of shear studs and small quantities of reinforced *insitu* infill at the ends of the slabs (see fig. 1-14).

The market for precast concrete floors in steel frames is huge – about 15 million sq.m in Europe alone. The construction details are well established, although they may not be the most economical or structurally efficient. Designers need to recognise the full implications of bringing the two elements together. Witness the following:

1) the reduced shear capacity of hollow core units supported on flexible steel beams. This is the result of bending perpendicular to the span of the floor unit which induces additional shear stress in the web. A design procedure for recognising and analysing the problem is given in the ***fib*** guide [2000].
2) the reduced shear capacity of interface shear studs when connecting hollow core units to steel beams. This is a consequence of the confined zone of stress in the gap between the ends of the hollow core units. A design method is given by Lam et al. [1998]
3) the problem of making a three edge slab support at gable end beams. The longitudinally supported edge causes torsion in the unit, which, as future R&D aims to show, may or may not reduce the shear capacity of the unit.

Hollow core units of 6 – 12 m span and 150 – 300 mm depth are used mostly in steel frames. If the floors are structurally isolated from the steel beam a horizontal diaphragm has to be provided either by steel cross bracing (below the precast units) or in a reinforced structural topping, noting that the tie forces in either case must be continuous and connected to the stabilising elements.

Figures 3-1 and 3-2 show examples of where there is no composite action between beam and slab. The overall depth is equal to the thickness of the slab plus the depth of the beam. Of course this may be the most economical solution in terms of steel beam design if floor depth is not a limiting criterion, as is the case in figure 3-2.

Fig. 3-1: Precast hollow cored floors in a steel and cast insitu frame. (Courtesy of University of Leeds, UK)

Fig. 3-2: Precast hollow cored floors in steel frame building

Attempts to reduce the overall floor depth are shown in figure 3-3 and in detail in figure 3-4. The ends of the precast floors must be specially shaped to enable to units to slot inside the beam, but this can be arranged with the producer at little extra cost. The bottom flange or leg of the shelf angle has to be long enough to allow shuffling of the unit back and forth between beams whilst maintaining safe bearings.

Insitu infill is poured into the gap between the ends of the slab and the steel beam to effectively 'lock' the floor units in position. If floor diaphragm action is required the ends of the slabs must be tied, in some way, to the steel sections – friction alone is not sufficient. The span-to-depth ratio for the total depth was about 25, compared with around 18 in the previous case.

Fig. 3-3: Precast concrete walls, columns and slabs integrated with steel columns and beams at Sky City, Sweden. (Courtesy of Strängbetong, Sweden)

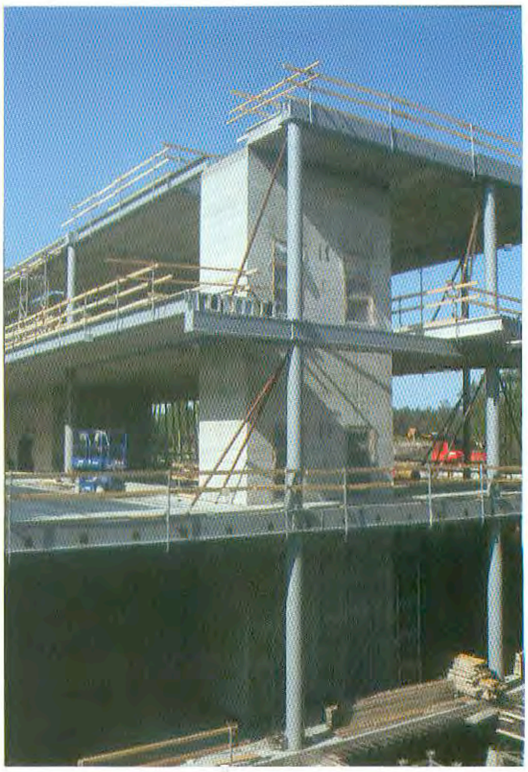
Fig. 3-4: Precast floors supported on the bottom flanges of rolled steel Universal beams or column sections. (Courtesy of Strängbetong, Sweden)

The main advantage in this technique, shown in figure 3-5, is to produce a (near) flat soffit, where the downstand is equal to the thickness of the bottom flange, say 15-25 mm. This form of construction is suited mostly to shallow floor units, i.e. hollow core in particular. Composite plank is rarely used because of their limiting spans (without propping) which tend to be less than 6 m.

The saving from having a flat soffit can be considerable, for instance claddings – ease of installing services. Height restrictions can mean that it is possible to fit another storey in the same overall building height. However, the cost of some sections (e.g. heavy Universal column or pile) can be much greater than that of a standard steel I-beam or precast inverted-tee beam, and so the economics must be judged.

The retail centre project shown in figures 3-6 and 3-7 illustrates both methods of top and bottom flange bearings. 400 mm deep prestressed hollow core units, spanning 15 m without structural topping, are supported either on the top of rolled Universal beams, or on the bottom flanges of prefabricated box sections.

Fig. 3-5: Long spans and a flush soffit are a feature of placing precast floor units onto the bottom flanges of steel beams. (Courtesy of Strängbetong, Sweden)



Figs 3-6 (left) and 3-7 (right): Concrete filled tubular steel columns and shallow prefabricated steel box beams support precast hollow core floor slabs. 'The Big Apple', Helsinki.

The circular hollow columns (shown in the photograph) were concrete filled. The ratio of the floor area (i.e. beam span x floor span) to total depth is about 100 m^2 per 500 mm depth. Horizontal stability was provided either by tubular steel cross bracing or cast *insitu* cores.

A compromise between the fully recessed and fully proud floor is to use shelf angles welded to the web of steel beams (Fig. 1-14). Figures 3-8 and 3-9 show the bottom and top view of this detail. The length of the leg of the shelf angle must be at least 100 mm. Note that the stability tie steel in the top of the slab must pass over the top of the beam (e. g. fig. 1-14), or else pass through predrilled holes. No composite action is considered in this case.

Fig. 3.8. Precast concrete floor units supported on steel shelf angles within the depth of steel beams. (Courtesy of Echo, Belgium)

Fig. 3-9: Continuity tie steel bars anchored into the longitudinal joints between hollow cored floors straddle across steel beams.

Prefabricated steel box beams (e. g. fig. 1-14) shown in figure 3-10, may use the bottom flange as the tension chord and side walls as the shear web such that the precast floor slab is designed to act compositely with the steel box beam. Holes in the side walls reduce carriage weight and enables tie bars to pass through from either side. The beams themselves may be designed as continuous by adding site placed rebars into the open shell of the beam. The span-to-depth ratio for the beam is 25-30.

Another type of steel soffit beam is shown in figure 3-11. A steel shell beam and a rebar cage is designed to support the self weight of hollow core floor units prior to the addition of small quantities of cast *insitu* infill to produce composite action with the rebar cage. Continuity top reinforcement is added to the ends of the rebar cage to form moment continuity over the column head. There is no moment transfer to the column. A similar approach is adopted in the tubular steel structure shown in figure 3-12 – but here the soffit beam is precast concrete and the rebar cage is formed into a truss. The addition of site placed reinforcing bars and cast *insitu* infill across the beams and columns creates continuity of both the slab and beam. The ratio of the floor area (i. e. beam span x floor span) to total depth is about 40 m^2 per 300 mm depth, for imposed loads of 5 kN/m^2.

Fig. 3-10: Precast hollow core floors recessed into steel box beams. (Courtesy of Teraspeikko, formerly Delta, Finland)

Fig. 3-11: A steel shell beam and a rebar cage supports hollow core floor units. (Courtesy of Addtek International Ltd, Finland)

Double tee (TT) floor units are not suitable for most of the examples shown in this Section, although there are a number of steel frame parking structures with TT floors. The greater span capacity of the TT unit, 20-30 m is generally not compatible with the spans used in steel frames. Underhand fixing beneath the top flange calls for splayed ends of around 300 x 150 mm triangular shape.

The top surface of the double-tee slab often protrudes above the top of the steel beam, and this rather defeats the objectives of recessing the units. This leads to the problem of carrying continuity tie steel across internal beams between the ends of precast units, and between the precast units and edge beams at external beams.

The main advantages and disadvantages in the various systems, which relate mainly to hollow core units rather than double-tee or composite plank, are given in Table 2-1.

Type of support	Advantages	Disadvantages
Shelf angles in rolled sections	Deep beams and shallow slabs More flexibility in using slabs of different type or depth	Shelf angle expensive Access to fixing may be difficult Composite action not common
Rolled UC flanges	Bottom flange parallel and wide for ease of fixing No additional fire protection required – the concrete floor absorbs the heat	UC is a 'heavy' section flexurally Range of UC limited Continuity tie steel difficult to fix No composite action
Prefabricated sections, e.g. box, 'top-hat'	Web openings reduce weight. Continuity tie steel passed through web openings. Ease of fixing slabs.	Steel beams flexible Temporary props may be required *Ad-hoc* manufacture required Design guidance not widely available
Prefabricated girder	Lightweight Easy access to *insitu* infilling Services routes may pass	Too flexible, may require propping

Table 2-1. Alternative solutions for precast concrete floors on steel beams

Fig. 3-12: Tubular steel columns support precast concrete soffit beam and rebar cages to form a truss to support precast hollow core floors. (Courtesy of CSP, Italy)

A special situation is shown in figure 3-13 where precast floor panels, spanning between concrete encased steel columns, are 8 m tall and 500 mm diameter. There are no downstand beams as the floor units are supported only at their corners. The soffit of the panels is exposed using strict blemish control. The exposed concrete surfaces also provide greater thermal capacity, contributing positively to the building's energy management and helping achieve a low energy concept.

Fig. 3-13: Precast floor panels span between concrete encased steel columns. (Courtesy of Trent Concrete Ltd., UK)

The main technical points to consider when using precast floors in steel frames are:

- Bearing lengths. The minimum bearing length for non-isolated floors (i.e. floors which are connected to prevent isolated failure) is 40 mm. The nominal bearing length for prestressed floor units which have tendon reinforcement continuing to the ends of the units is therefore about 60 mm. Where reinforced floor slabs have end cover to reinforcement of, say 30 mm the nominal bearing length is 75 mm.
- Bearings onto shelf angles need to be at least 75 mm to enable the unit to be manoeuvred into position beneath the top flange. The ends of hollow core units are chamfered for a length of about 300 mm to assist in this operation. The bearing is normally laid dry.
- Tolerances. Prestressed hollow core floors are manufactured to an accuracy of maximum ± 10 mm. This is within the normal tolerances expected of steelwork.
- Floor diaphragm action. A structural connection must be made between the floor plate and the beams in order to transmit horizontal forces between the steel frame and precast floor. If the floor units are positioned within the depth of the beam the ends must be concreted in solidly. Tie steel coupling the floor units to the beams must be provided to cater for the shear stress at the ends of the floors. Concrete-steel contact friction is not sufficient nor elastically recoverable in case of debonding or breakdown. If this is not satisfied horizontal bracing must be provided by the steel frame.
- Full or partial interaction between beams and floor units may be provided by mechanical connections.
- The steel beam should be checked for torsion where the beam is carrying the floor units on one side only. Temporary propping may also be required during erection.

3.3 Steel decking on precast concrete beams

Although the developers of steel profiled (metal) decking certainly had structural steelwork in mind as the support, this form of composite steel-*insitu* concrete flooring may equally be used with precast concrete support beams. In the project shown in figures 3-14 and 3-15 steel decking of up to 4 m span was simply supported and recessed below the tops of 16 m long pretensioned precast beams. Faced with minimising floor zones over large spans the reinforced concrete beams cantilevered some 4 m beyond the outer yokes and supported lightweight profiled metal decking. The service-plus-structural zone of 950 mm included 300 mm for M&E services. This was achieved by locating the steel decking mid-way down the beam depth resulting in a favourable span-depth ratio for the beams of 19:1. In this way shear walls and shear cores were not required, enabling large open plan office accommodation.

Fig. 3-14: Profiled metal decking spans between precast beams supported on cast insitu columns. Bracken House, London (Courtesy of Trent Concrete Ltd. UK)

Fig. 3-15: Profiled metal decking supported on cantilevered precast beams. Bracken House, London (Courtesy of Trent Concrete Ltd. UK)

The main advantages in using steel decking, as opposed to say hollow cored floors, is to reduce vertical transportation and crane hook-up times in tall buildings, and to allow a greater freedom in the sizes and positions of service holes. However, the time and resources need to pump or hoist large quantities of *insitu* concrete (typically 200 kg/m^2) and site fix the reinforcing mesh (about 2 - 3 kg/m^2) must be justified in favour of a precast floor. Its limiting spans, typically 4 - 7 m for 150 - 200 mm deep floors, actually makes profiled steel decking more suited to tertiary steel frames rather than the longer span floors found in precast frames.

It is also easier and cheaper to specify non-rectangular metal decking, which can be cut on site. Irregular shapes are sometimes a drawback in wide slab precast flooring units.

Metal decking can be combined with tertiary prestressed beam & floor systems, e. g. in Figure 3.16, where secondary beams are spaced about 3 m apart. The infill flooring may be composite steel decking. The secondary beams thus become composite with the *insitu* topping. This method is extremely flexible as the steel decking can be cut to suit non-rectangular framing. Services may be concealed within the topping thus reducing further the floor zone. (Seasoned timber or fibre cement sheets may also be used as the flooring, although in such cases beam centres would be less than 1.5 m.)

Although precast wide slab floors are relatively lightweight, typically having voids of 50 % of the cross sectional area, and structurally efficient in terms of load-span, there are many situations where the units are not utilised to their full structural capacity. For example, when fully stressed a 1200 mm wide x 200 mm deep hollow core unit may have a moment capacity of 100 kNm, but the requirements of a project may only be, say, 75 kNm. Thus the fully stressed unit could operate over a width of 1200 x 100/75 = 1600 mm such that infill materials could be supported by the hollow core unit over a width of 400 mm. Shear is unlikely to be a governing factor, but the deflection must be checked to ensure that the hollow core unit can sustain the additional service load.

Fig. 3-16: Steel profiled decking mixed with tertiary precast beam and slab.

This is the principle of the beam-and-block floor, but is also basis for the cross section of the floor shown in figure 3-17. Special edge profiles to the hollow core unit are required. A structural topping is necessary so that the hollow core unit may be designed compositely to further increase strength and provide a diaphragm floor. The system gives spaces for services beneath the tray, especially crossovers at service ducts. The cost of the infill pieces should be considered against that of a complete precast floor, as should the safety aspects (guard rails) of leaving wide openings in the floor. (The bridging unit can also be made using timber to reduce weight and facilitate fixings for services.)

The main technical points to consider when using metal decking on precast beams are:-

- Bearing lengths. The minimum nominal bearing length is taken as about 50 - 60 mm because the structural *insitu* concrete topping (with continuity reinforcement) provides an extended bearing in the final condition.
- Continuity steel is required for diaphragm action and stability purposes. This may be provided across the top of the beam or through preformed holes in the web.

- Shrinkage cracks in the longitudinal direction of the interface should be controlled by the minimum recommended area of continuity tie steel, and a low free water content in the concrete.
- Composite action between the beam and the structural topping may be considered provided interface shear reinforcement is provided.

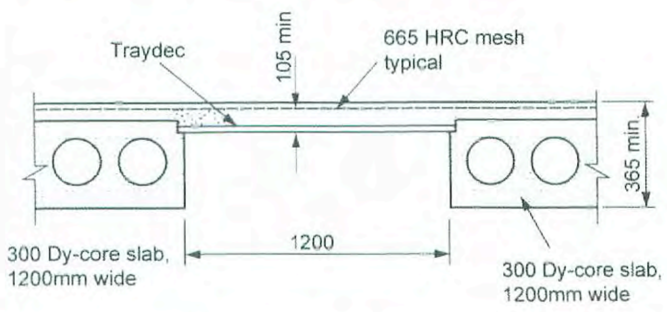


Fig. 3-17: Steel profiled decking spanning between precast hollow core floor units

3.4 Structural steelwork and precast concrete frames

Structural steelwork and precast concrete has been combined in many different ways:
1) steel beams on precast columns,
2) precast spandrel beams on steel columns,
3) steel portal roof frames onto precast concrete structures,
4) steel rafters and sheeting rails onto precast columns,
5) hollow core wall panels on to steel frames.

Deep precast concrete spandrels are used to form the exterior dry envelope to the rectangular hollow columns shown in figure 3-18 where rapid weather closure can be achieved in the window space. The effective length of the column is greatly reduced when a shear connection is made between the top and bottom of the concrete spandrel.

Fig. 3-18: Precast concrete spandrels and hollow core flooring in a steel frame near Stockholm, Sweden. (Courtesy of Strängbetong, Sweden)

Fig. 3-19: Insulated precast concrete spandrel units and precast shear cores in a steel frame near Stockholm (Courtesy of Strängbetong, Sweden)

Frames such as these may be braced either by steel bracing or by concrete shear walls as shown in figure 3-19. Double-skin cavity insulated precast walls were erected between steel columns. Architectural concrete, such as the white spandrel beams in exposed aggregate shown in figure 3-20, provide both the exterior façade to the steelwork frame, thermal insulation, as well as the edge support to the precast floors.

Fig. 3-20: Exposed finish panels on a steel frame

Steel-to-precast concrete beam connections are most commonly designed as pinned because designers are still unsure about achieving the tolerances necessary to specify a moment resistant connection. However, moment connections may be formed at cantilevers, often by designing a deep haunch as shown in figures 3-21 and 3-22. Threaded sockets may be accurately cast into the precast columns to await site bolts at the haunch. Other types of fixings for structural steelwork can easily be accommodated in precast concrete columns, beams and wall elements. This is because most precast elements already utilise steel inserts or cast-in-sockets in their connections to other precast members.

Fig. 3-21: Structural steelwork to precast concrete connection details

It is important to allow for tolerance in three dimensions, e. g. by using shims, slotted holes etc. The sloping steel mansard roof shown in figure 3-23 was simply pin jointed through a small steel base plate bolted to the top of the precast columns. The main problems occur where connecting members are not coincident with the framing grid and connections are required off of the floor slab – a situation which should be avoided with hollow core units.

Fig. 3-22: Cantilever steel roof making a moment connection to precast columns (Courtesy of Composite Structures, UK)

The permutations for the design of connections are so numerous that any of the details used for wholly precast or structural steelwork connections can be modified to suit mixed construction. For example, in Figure 3.24 the narrow plate end connector in the precast beam mates to a stiffened bracket welded to the sides of a rolled hollow (concrete filled) steel column. A small weld is made between the two steel sections and the connection is designed as pinned jointed. The triangular end shape of the beam is not essential - a rectangular end profile could be used.

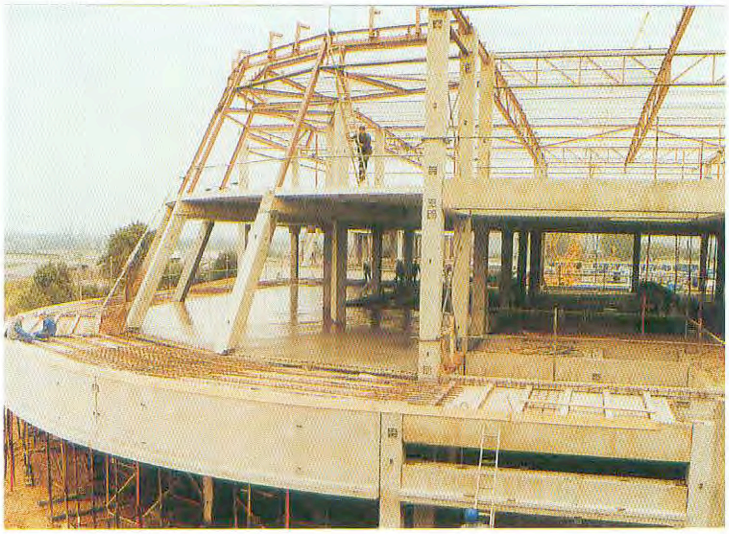


Fig. 3-23: Steel mansard roof on to a precast concrete frame (Courtesy of Composite Structures, UK)

Fig. 3-24: Beam-to-column connection between tubular steel column and precast beam

Large space portal frames for industrial warehouses, e.g. span > 25 m, height > 10 m, are designed in some countries using precast concrete columns (occasionally pretensioned for handling) with long span steel trusses. The columns are designed as moment resisting cantilevers of large capacity, and may be rectangular or I section.

The 25 m high columns (rear of photograph) in the project shown in figure 3-25 are of I section with tapered flanges – but, at 18 tonnes each the cost of transportation and craneage was considerably greater than equivalent steel column. However, the columns are torsionally stiff and when the cost savings in materials and fixing of lateral bracing etc. are considered the precast solution is likely to be cheaper.

In the industrial warehouse in figure 3-26 the precast portal frame and roof is clad in thin metal sheeting, insulated and colour coated. The purlins and sheeting rails may be in either precast concrete or cold rolled steel.

Grandstands for sports stadia are an obvious form of steel and precast. Massively damped spectator structures consist of a mix of cast insitu and precast concrete (often post tensioned for lateral stability), usually for the vertical and horizontal components, respectively. A mixture of heavy steel raker beams and precast concrete L-section bleachers (terraces) are

Fig. 3-25: Steel trusses atop 25 m high prestressed precast concrete columns (Court. Composite Structures, UK)

Fig. 3-26: Precast concrete portal frame with steel sheeting, purlins and side rails (Courtesy of Parma Betonila, Finland)

often used. Figures 3-27 and 3-28 show a popular solution for stadia design - to cater for dynamic loading the concrete frame is designed so that its flexural stiffness is disproportionately greater than its strength, compared with static loading.

The roof structure is designed to be more flexible and this gives rise to lightweight steel trusses or lattices supported in a variety of ways - single bay cantilevers, arches, tensioned structures, transversely spanning trusses and so on.

The main technical issues concerning steel frames in precast concrete construction are:

- Tolerances. There is comparable accuracy between precast and steel frames, such that no special provisions need to be made. The usual provision for levelling shims and slotted holes for adjustments are commonplace.
- Holding down bolts. If these are securely cast into the top of columns tolerances of ±20 mm should be made in steel base plates. If the bolts are free to move (by prior arrangement with the precast manufacturer) the tolerance may be less.

- End rotations. End rotations (due to flexure) in steel beams may be greater than in equivalent strength concrete beams. This should be considered in the design of pin jointed connections.
- Very long span steel rafters should bear onto compressible material to prevent contact pressures between the rafter and column due to end rotations.
- Thermal movement. Thermal expansion of steelwork is similar to that of concrete such that no additional precautions, to those in force for precast concrete, are necessary.

Fig. 3-27: Balanced steel beams forms the roof on top of a precast grandstand structure (Courtesy of Parma Betonila, Finland)

Fig. 3-28: Steel roof beams cantilevered from the top of precast concrete columns

3.5 Precast facades in steel frames

Non-loadbearing precast cladding has been used in the exterior facades of steel structures in several different modes, for example:

- storey height panels, with prefabricated insulation (sandwich panel, fig. 3-29)
- building height/width panels (always insulated), spanning either:
- vertically from ground beams to roof structure (fig. 3-30),
- horizontally between steel column (fig. 3-31).

These panels resist only self weight (gravity) forces and horizontal wind loads, and as such are not highly stressed. The design is governed by thermal insulation criterion. Panel sizes are limited by the handling capacity of the manufacturing plant and site crane, transportation restrictions, and the spacing of steel members rather than by the strength of the panel. Maximum heights are around 15 m, where in order to prevent cracking during handling, the panel would be lightly pretensioned. To connect to steel frames panels are designed either a hanging or bearing, i.e. they are hung from lintels or seated onto bearer beams with the remote end sliding to allow for movement. Bearing connections are designed with greater tolerances because of the difficulties with making corrections if the beam is misplaced etc. [PCI, 1997].

The main technical issues concerning precast façade panels in steel frames are:

- Standardised details and fixing tolerances. The same comments are made as for cast insitu frames.
- Flexibility of steel beams. The flexural stiffness of steel beams should be sufficient to enable the precast concrete panels, typically weighing 1 – 2 tons per m, to be accurately positioned horizontally. The steel beam should not move after the panel has been fixed.

Fig. 3-29: Storey height precast façade panels on a steel framed structure (Courtesy of Trent Concrete Ltd. UK)

3.6 Summary of chapter 3

The very wide application of structural steelwork and precast concrete was demonstrated. The most popular and successful combination has been long span prestressed floors supported on shallow steel beams, and lightweight steel roof trusses or beams on precast concrete frames.

Fig. 3-30: Vertical precast sandwich panels used in steel frame warehouses, stadia etc. (Courtesy of PCI, USA)

Fig. 3-31: Horizontal hollow core wall panels used in a steel frame warehouse (Courtesy of Echo, Belgium)

The main reasons why steel has been successfully incorporated in to precast construction is down to three main factors.

1. Steel can be rolled to very thin open or closed sections, but when it is laterally and torsionally restrained by precast floors etc. it can be designed for its full plastic capacity.
2. Steel can be fabricated in to lightweight roof trusses which span distances commensurate with the spans achieved in the precast floors below.
3. Fire resistant materials do not need to be applied to steelwork which is supporting a concrete floor, as the latter acts as a 'heat-sink'.

It is likely that structural engineers will have a bigger influence over this type of construction as many of the details specific to the precast-steelwork interface are better resolved by engineers than architects or fabricators.

4 Precast concrete mixed with timber

4.1 Timber roofs on precast structures

As with steelwork, timber is ostensibly used to replace precast concrete for long span roofs and lightweight floors – the two extremes being attributable to timber's good strength-to-weight ratio. Although its market share in mixed multi-storey buildings is probably less than 1 or 2 per cent, it is growing rapidly especially in parts of the world where timber and precast concrete are both 'local' materials, e.g. central Europe, Scandinavia and the Far East.

Recent developments have resulted in economical and architectural advances in nail plate fin trusses and glue laminated (*glulam*) beams. In the past 15 years timber has taken some of the market for steel lattice roofs, especially in the 1990's when the relative price of timber-to-steel has dropped and availability increased. The erection time for a timber roof is comparable with steel as the amount of temporary bracing is similar. Haulage and hoisting costs are about the same.

The use of simply supported timber trusses is shown in figures 1-6 and 4-1. Spans of up to 30 m are supported on rectangular precast beams with an intermediate timber batten. The grade of timber is mostly general grade softwood (pine, cedar, larch) with a bending strength parallel to the grain of around 8 to 15 N/mm^2. The relative volumetric movement (e.g. due to temperature and moisture loss/gain) between reinforced concrete and timber is small. Relative displacements are catered for in slotted holes at the connection. Galvanised steel brackets in which the timber beams are simply supported may be bolted to the sides of precast beams or columns. It is unusual to design moment resisting or semi-rigid connections.

Fig. 4-1: Timber rafters fastened to battens on a precast concrete frame.

Glulam construction may be used for complete roof structures. In figure 4-2, a glue laminated timber space truss forms the roof over a precast concrete structural frame and terrace units concrete at the Pavilhão Utopia/Multiusos at Expo '98 in Lisbon. In figure 4-3 the *glulam* beams were dowelled to the column head in a manner akin to precast beams. *Glulam* rafters, supported on galvanised steel chairs, impose torsion in the beams and column head connection.

The *glulam* rafters shown in the structure in figure 4-4 were supported off precast concrete column head (centre) and on short steel pillars bolted to the top of precast columns (edge).

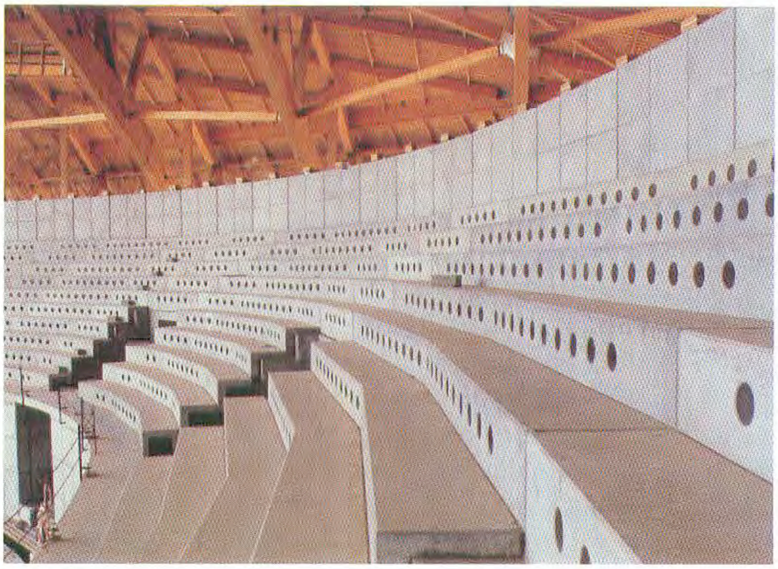


Fig. 4-2: Glue laminated timber space truss provides the roof to a precast structure at Lisbon's Expo '98 site. (Courtesy Prégaia, Portugal)

Fig. 4-3: Glue laminated beams and rafters provide the roof to a precast concrete supermarket structure. (Courtesy of Ergon, Belgium)

Glulam timber is a major feature of one of the most impressive mixed structures in recent years, illustrated in figures 4-5 to 4-7. The structure comprises:-

- *glulam* roof beams or trusses (fig. 4-5),
- sheet metal roof cladding,
- precast concrete framework and flooring,
- post-tensioned cast insitu columns to roof support,
- steel nodes at column heads (fig. 4-6),
- cast insitu basement and foundations,
- planar glass walls (fig. 4-7).

Although some 35 different schemes were considered for this structure, the timber and precast concrete satisfy both the structural and architectural requirements, as well as being locally available materials.

Fig. 4-4: Glue laminated timber rafters supported off precast concrete columns in a parking structure. (Courtesy of Strängbetong, Sweden)

The reaction from the roof is predominantly horizontal giving rise to the triangular steel nodes and moment resisting columns. The internal precast framework is practically an independent structure.

Fig. 4-5: Glue laminated timber rafters supported off precast concrete columns at Oslo International Airport. (Courtesy of Spenncon, Norway)

Many of the technical issues relating to steelwork and precast also affect the combination of timber and precast concrete. These are:

- Tolerances, thermal and shrinkage movement. These are essentially the same as steel provided that the timber is at a correct moisture content.
- End rotations. Timber beams have a much smaller stiffness-to-strength ratio than steel beams, which, for equal bending capacity, create larger flexural end rotations, especially under fluctuating live load.
- Spring-back and creep in curved glue laminated trusses produces additional forces at the connection which must be catered for.

Fig. 4-6: Interior view during construction of precast frame and timber rafters at Oslo International Airport. (Courtesy of Spenncon, Norway)

- Novel connections should be avoided in favour of manufacturer's recommendations.
- Direct connection to column head is favoured more than a side connection.

Fig. 4-7: Structural timber and glazing systems supported from the precast frame at Oslo International Airport.

4.2 Precast floors and timber frames

Glue laminated timber columns may be used to support precast flooring, as shown in Figure 4.8 and 4.9 in a warehouse building in Scandinavia. These storey height columns were stabilised using precast cores, and by timber cross bracing in the temporary stage. They supported beams in one direction carrying 6 x 3 m precast concrete floor units.

Mixed timber (in the roof and façade framing), masonry (load bearing walls) and precast concrete (floors) is a unique mixture shown in figure 4-10. As in the previous, but totally different, case study each material is working optimally both in terms of strength and buildability.

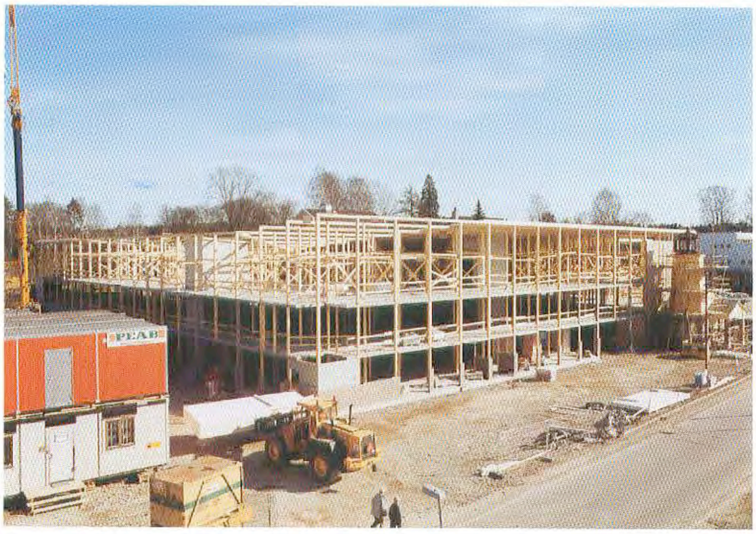


Fig. 4-8: Glue laminated timber beams and columns support precast flooring in a warehouse (Courtesy of Strängbetong, Sweden)

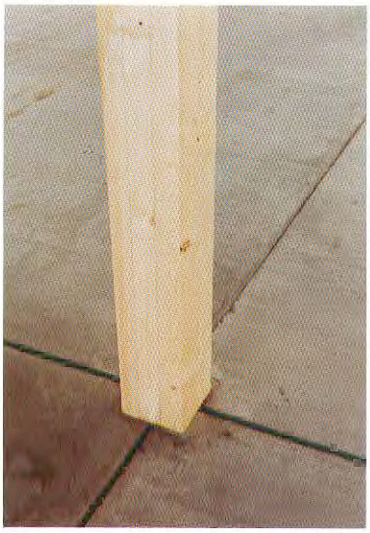


Fig. 4-9: Detail to the column-floor joint in figure 4-7. (Courtesy of Strängbetong, Sweden)

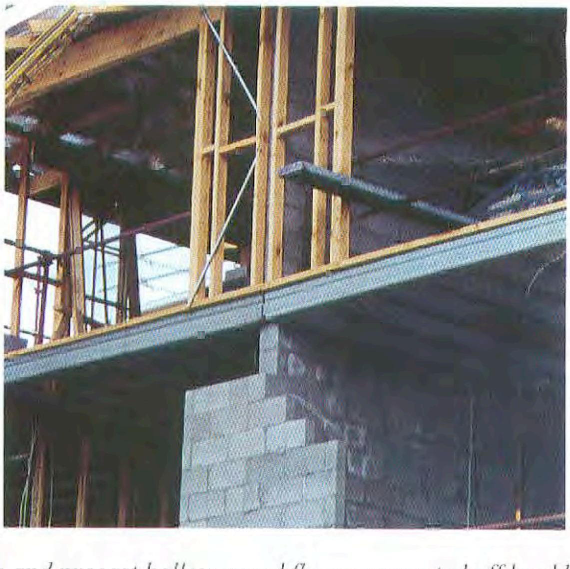


Fig. 4-10: Timber roof beams and precast hollow cored floors supported off load bearing masonry (Courtesy of Cement & Concrete Association of Australia)

4.3 Timber floors and precast walls in housing

In figures 4-11 and 4-12, the precast walls are provided for strength and acoustic isolation between dwellings. Large prefabricates in concrete and high quality timber speeds up construction rates and fulfil housing demands.

Fig. 4-11: Timber floors and precast concrete walls used for domestic dwellings. (Courtesy C&CA of Australia)

Fig. 4-12: Timber roof trusses and precast concrete walls used for domestic dwellings in Scandinavia.

4.4 Summary of chapter 4

The potential for mixed precast concrete and timber is increasing as the technology behind developments in glue laminated timber moves forward with each successful project. In spite of the fact that the design of connections between concrete and timber is not well documented – there are no codes or standards for this, and little data on the relative movement of the two materials (e.g. thermal, spring-back in curved members) engineers have successfully used this combination in a number of exiting projects.

The most recently developed combination has been long span *glulam* trusses and beams on to precast frames, and the use of precast concrete acoustic walls in timber houses. It is anticipated that in certain countries in a few years the number of contemporary case studies will rival that of steel-and-precast.

5 Precast concrete mixed with masonry

5.1 Precast concrete floors on masonry walls

The most fundamental of all mixed construction is where load bearing masonry walls supports long span precast concrete floors. Frameless construction comprising brick or block walls of between 90 and 200 mm thickness support the following types of reinforced and pretensioned floor units:

- 600 to 1200 mm wide hollow core units (figure 5-1),
- precast beam and block floors (figure 5-2),
- precast composite (permanent formwork) floors (figure 5-3).

The method is very common even though there is a little direct design and construction guidance. Most information tends to be provided by the precast floor manufacturer. The main problem concerns inadequate bearing lengths, particularly as extended bearings are not provided. This is because of cumulative tolerances due to either short length precast units bearing on to out-of-plumb walls.

Nominal bearing lengths are normally specified as 100 mm. The bearing strength of the precast units is less critical than that of the walls as the strength of the wall may only be around 10 – 15 N/mm^2 when the floors are laid. Units should be bedded on bearing fillers of around 3 mm thickness, such as wet mortar bedding or elastomeric strips.

Fig. 5-1: Load bearing masonry blockwork supporting long span prestressed hollow cored floors. (Courtesy of Tarmac Topfloor, UK)

Floor diaphragm may be carried across precast floor units (such as hollow core units) that are positively tied together at their ends, using site placed reinforcement cast into milled slots. If the structure in question is a load bearing wall frame, it is unlikely that the span of the diaphragm will exceed 10 to 15 m, in which case horizontal diaphragm forces will be small. However this option is rarely considered by designers because of the need to provide shear friction and perimeter tie steel bars which cannot pass across cavities. Floor diaphragm forces may not be carried across beam and block floors.

Precast floors may pass over intermediate supports only if the floor unit is sufficiently flexible to bed on to the interior support, such as the permanent formwork units in figure 5.3. The floor can be reinforced to carry hogging moments developed over an interior support. The support is usually at mid-span. This reduces imposed sagging bending moments by a factor of 8 compared with the simply supported case. Propping the floor may be costly and technically difficult to achieve with confidence. However it may be economical overall if the precast floor units are sufficiently lightweight and long to reduce haulage costs and hoisting times.

Fig. 5-2: Load bearing brickwork supporting precast beam and infill block floors (Courtesy of Cement & Concrete Association of Australia)

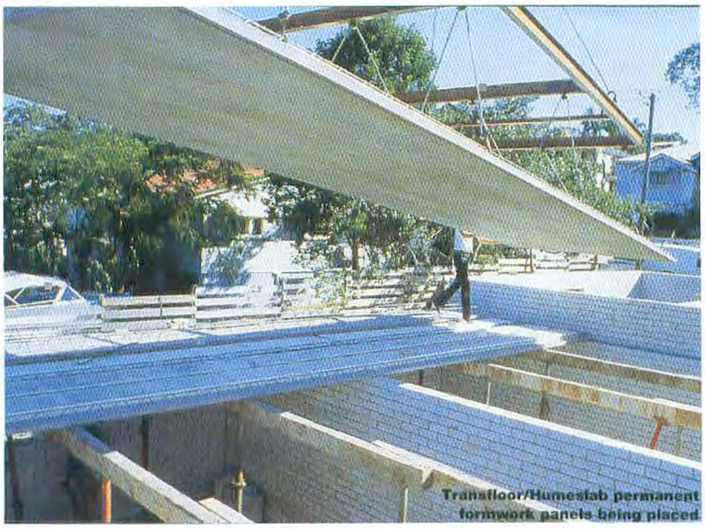


Fig. 5-3: Permanent precast concrete formwork ('half-slab') floor units spans across an intermediate brickwork wall (Courtesy of Cement & Concrete Association of Australia)

Recent trends towards increased prefabrication of masonry in Benelux countries have lead to the so-called 'Dutch block' wall, shown in figure 5-4. The blocks are bonded by chemical glue. This wall may sustain the loads from thermally insulated precast hollow cored floors of some 6 – 8 m span. The floor units require no interior support, thus removing internal partitions from the critical construction path. The speed or erection of these prefabricates is around 600 m^2 area per week.

Precast partition walls and precast hollow cored floor units, up to 12 m long, form the major compartments in domestic dwelling shown in figure 5-5. Infill masonry – both brick and blockwork, is used to complete each dwelling.

Fig. 5-4: Silica block walls support precast concrete hollow cored floors in low rise dwellings (Courtesy of VBI, Netherlands)

Fig. 5-5: Precast partition walls and load bearing brickwork support precast hollow cored floor units in low rise dwellings (Courtesy of VBI, Netherlands)

5.2 Precast concrete and masonry in structures

This topic may be divided into two distinct, and very different subjects:

1. masonry (brick, tiles etc.) applied to precast façade panels or structural elements, beams, spandrels, columns,
2. masonry walls used to stabilise or otherwise infill precast sway frames.

Insitu masonry is used extensively as the exterior façade to precast concrete frames – especially where brick is plentiful and the weather conducive to this form of construction, e.g. excludes Scandinavia and some parts of central Europe. As the masonry facade is chiefly weather protection it is not discussed in this publication. However brick, stone or tile may be applied as a decorative finish to structural or non-structural precast concrete facades and frames. Brick slips or half-cut bricks are bonded into the concrete to restrain differential movement so the bricks will not de-bond. The panels may be used as the foundations to insitu brickwork and are often used to buttress brick arches. The technology is well established and documented [Taylor, 1992].

Fig. 5-6: Structural precast concrete spandrel beams with integrated brickwork façade (Courtesy of Trent Concrete Ltd., UK)

In figure 5-6 the structure was clad with storey height panels forming the inner skin. At window openings casting them integrally with the panels (inset) brick arches and heads are formed. Internal works were allowed to proceed with weather delays. Other brick faced precast concrete units included cornices, gutters and planting boxes.

Precast masonry and concrete were combined in a decorative, yet structurally load bearing, panel and pillar construction shown in figure 5-7. Reconstructed red sandstone panels to the upper levels include black granite string courses, whilst the first floor brick-faced precast panels rise from ground floor brickwork.

Further external elevations and views are shown in figures 1-3 and 5-8 of the mixed masonry, precast and steel roof structure at the Inland Revenue building (introduced in chapter 1)

The storey high piers were of solid brick (with the exception of grout tubes which accommodated lifting bars) and were transported to site in a vertical position to be lifted directly into place onto pre-levelled packs. The unique combination of prefabricated brickwork piers, precast pier caps and floor plates proved extremely accurate and fast to build. Precision engineered steel and timber moulds, were used to cast the arched soffit floor units. Moulds were prepared to cast a matt texture onto the ex-mould surfaces, which were designed to receive directly applied paint as shown in figure 5-9.

Infill masonry is occasionally used as the shear wall in precast frames of up to about 7 - 8 storeys. The height depends on the layout of the building and the number and size of walls available (fig. 5-10).

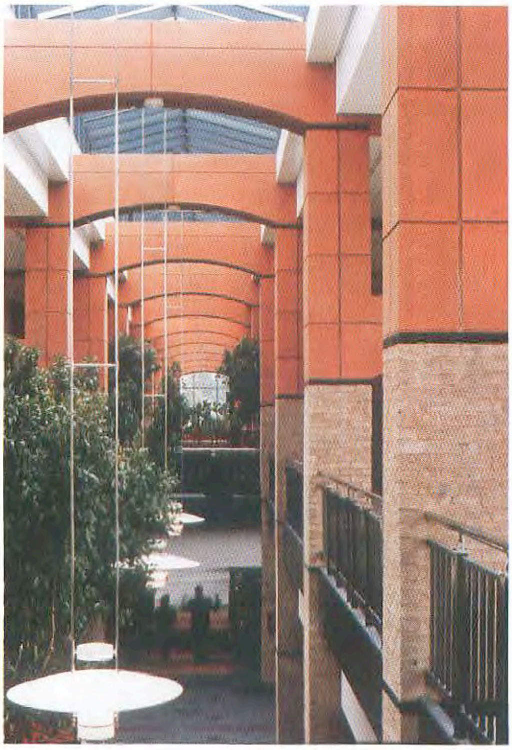


Fig. 5-7: Prefabricated brickwork pillars support architectural precast concrete arches (Courtesy of Trent Concrete Ltd. UK)

Fig. 5-8: Prefabricated brickwork pillars support precast concrete floors and steel roof at the rotunda, Inland Revenue, Nottingham, UK.

It is unclear whether this is 'composite construction', because the precast structure relies on composite action with the wall, or whether it is 'mixed construction' as the capacity of the wall is determined ostensibly from the properties of the brick and mortar. In low-rise frames the infill may be of solid concrete block – lightweight or hollow blocks are not recommended.

Insitu load bearing masonry walls are rarely used to carry precast concrete frame elements (beams, columns) because of on-site fixing sequences - the speed of erection of a precast structure is too rapid for the strength development of the load bearing masonry. Occasionally masonry walls are built to support a special item, such as a lift motor room floor, which is not on the critical path of the frame erection.

Fig. 5-9: Interior view of prefabricated brick pillars and exposed precast floor units at Inland Revenue, Nottingham, UK. (Courtesy of Brick Development Association, UK)

Fig. 5-10: Infill brick walls used to stabilise pin-jointed precast concrete frames

5.3 Summary of chapter 5

This chapter has considered the many obvious, and less obvious, combinations of brick and block masonry with precast concrete structures and floors. Although the technology is well established and has been popular for 30-40 years, there is still a lack of codified data concerning many of the details used. Most of these tend to be by rule-of-thumb, or plain experience.

Although the most common combination is to use prestressed floors on load bearing walls, this contrasts with multi-storey masonry pillars supporting vaulted precast floors and steel rafters found in other exiting projects.

6 References

Barker, T.; Guthrie, A.; Noble, N.; Rice, P. [1983], *The Menil Collection*, Houston Art Gallery, Arup Journal, Vol. 18, No. 1, pp 2-7.

Charlesworth, G. L. et al., [1995], *Thurrock Lakeside Car Parks,* Reinforced Concrete Council, British Cement Association, UK, 13 p.

Evans, B., [1993], *Prefabricating the Superstructure*, Architects' Journal, UK, 16 June 1993, pp 41-52.

fib – guide to good practice *Special design considerations for precast prestressed hollow core floors*, ***fib*** Bulletin 6, Fédération Internationale du Béton, [2000], Lausanne, 180 p.

FIP Guide to good practice *Composite floor structures,* Fédération Internationale de la Précontrainte, [1998], SETO, London, 58 p.

Goodchild, C. H., [1995], *Hybrid Concrete Construction*, Reinforced Concrete Council, British Cement Association, UK, 64 p

Lam, D.; Elliott, K. S.; Nethercot, D. A., [1998], *Push-off Tests on Shear Studs with Hollow Core Floors*, The Structural Engineer, London, Vol. 76, No. 9, pp 167-174.

Talyor, H. P. J. et al., Editor. [1992], *Precast Concrete Cladding*, Arnold, 307 p.

PCI Journal, [1997], *State of the Art of Precast / Prestressed Sandwich Wall Panels*, Vol 42, No. 2, 60 p.

Vambersky, J. N. J. A., [1996], *VNO / NCW Office Building*, The Hague, Netherlands, FIP Notes, Vol. 2, pp 15-18

Vambersky, J. N. J. A., *Hybrid Structures – Solutions and Opportunities*, www.corsmit.demon.nl/vam.html

ISSN 1562-3610
ISBN 2-88394-059-2

Precast concrete in mixed construction

Contents

fib CEB-FIP
fédération internationale du béton
the international federation for structural concrete
created from the merger of CEB and FIP