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HIGH-RISE EARLY DESIGN STUDY
STAGE 1

Prepared For:

EcoSmart CONCRETE PROJECT
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Vancouver • Victoria • Calgary • Edmonton • Toronto

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1.0 INTRODUCTION

Read Jones Christoffersen Ltd. was one of two consulting structural engineering firms engaged by the Globe Foundation of Canada to participate in the Stage 1 – High Rise Early Design Study on behalf of the EcoSmart Concrete Project.

The other firm selected to undertake this review was Yolles Partnership Inc. of Toronto. Read Jones Christoffersen Ltd. met with Yolles earlier on in the study in order to divide the structural systems to be reviewed to avoid duplication in this study and, therefore, maximize the number of systems reviewed on behalf of EcoSmart.

The objective of the EcoSmart Concrete Project is to minimize greenhouse gas emissions to the atmosphere by replacing Portland Cement in the concrete mix with Supplementary Cementing Materials (SCM) to the greatest extent possible while maintaining and improving cost, performance and constructibility. Previous reports prepared by Fast + Epp Structural Engineers,[1] and Busby + Associates Architects,[2] had indicated that the increased use of supplementary cementing materials on the slab portions of high-rise residential construction was problematic due to the extended cure time required for such concrete. This extended cure time meant that in normal cast-in-place reinforced concrete construction the formwork could not be stripped as quickly as with a normal concrete mix. This delay in the formwork stripping extended the construction schedule to a point that the use of SCM's was no longer economically viable in this form of construction.

[1] High volume fly-ash concrete usage for high-rise construction by Fast + Epp Structural Engineers dated November 2000

[2] Use of EcoSmart concrete in the Bayview high-rise apartment, Vancouver, B.C., prepared by Busby + Associates Architects, November 2002.

This is particularly frustrating in the use of SCM's as studies indicate that two-thirds of all building concrete comprises the horizontal elements and that the tower slabs comprise of 40% of the total concrete in the project. An inability to utilize SCM's in these components of a typical high-rise building severely limits its application to the construction industry.

2.0 SCOPE OF STUDY

The objective of this study is to investigate alternative structural slab systems for a typical high-rise residential building in Vancouver that could use increased levels of SCM's to replace normal Portland Cement in slab construction as outlined in the Terms of Reference of this study.

"The objective of the study is to produce the required knowledge for understanding the relationship between the selection of a high-rise building structural system and its environmental performance, cost and constructibility (i.e. the principles of EcoSmart)."

"The goal of this study is not to design new systems for high-rise construction; instead it is to compare available proven technology based on the principles of EcoSmart."

The Terms of Reference of the EcoSmart Project is that it addresses three desired outcomes:

Early Stage: Develop design methodologies that take EcoSmart concrete properties into consideration at the time the structure is designed.

De-Materialization: Identify material reduction opportunities by using a smaller amount of better performance concrete or by using precast elements when possible.

High-Rise Construction: The fast setting requirements associated with high-rise construction make it very challenging to apply EcoSmart Concrete to this important market. The project will search solutions to this issue, both by looking at traditional cast-in-place methods and by investigating novel approaches such as hybrid steel/concrete system. The project will invest in the additional research and design work necessary to produce a real case study using three innovative building design methods.

At least three floor framing systems, one from each of the following three groups, are to be evaluated:

.1 Traditional cast-in-place concrete.
.2 Conventional precast or hybrid concrete precast.
.3 Steel, or hybrid concrete steel, or other systems as proposed by the consultant.

A particular building floor plate was created and utilized as the case study. The floor plate originally proposed was revised to conform more closely to a typical Vancouver residential tower. This building is to represent a typical high-rise condominium project located in downtown Vancouver. It is 22-storeys in height with a floor plate as indicated in the attached outline. The building height is specified in terms of a clear interior room height of 2,400mm. The exterior envelope is assumed to be a full height double-glazed window wall cladding system commonly used in this type of building construction in Vancouver. Alternative comparable building cladding systems can be suggested as part of the study in order to ensure compatibility with selected structural systems. There is a requirement that mechanical ducts be incorporated into the floor system with an average area of 8,000 mm^2 in cross section. There is also a requirement that the acoustical sound transmission rating be a minimum of 52 STC for the floor and the floor to have a minimum 2-hour fire-rating.

The Stage 1 part of the project, as outlined in this report, documents a description of the structural system with schematic drawings of the floor slab for one system of each of the three categories required.

The work was undertaken in both Read Jones Christoffersen Ltd.'s Toronto and Vancouver offices under the direction of Ronald Mazza, P. Eng., a Principal in our Toronto office, Diana Klein a project engineer in our Vancouver office, and Ralf Altenkirch a design engineer in our Toronto office. Both Diana and Ralf worked as designers on this project.

Upon completion of the review of the Stage 1 report, one of the two selected engineering firms will be selected to proceed in Stage 2 with a more detailed study of the selected structural systems from an environmental performance, economical, and constructibility point-of-view.

3.0 STRUCTURAL SYSTEMS REVIEWED

The systems selected by Read Jones Christoffersen Ltd. in their division of labour with Yolles are as follows:

.1 Cast-in-Place Concrete

- (a) Lift Slab Construction
- (b) Post-Tensioned Construction

.2 Precast Concrete

- (a) Hybrid Precast /Cast-in-Place Concrete Deck
- (b) PRESSS

.3 Hybrid Steel and Concrete System

- (a) Hambro Joist System

In each of the three studies reviewed, the primary system reviewed will be system (a) in each of the categories. System (b) will be reviewed in less detail and with a general description of its potential and limitations in each of the sections.

3.1 CAST-IN-PLACE CONCRETE

(a) Lift Slab Construction

History

The concept of lift slab construction originates in Columbia, South America and in the United States as the Youtz-Slick lift slab method in the 1950's. It was generally used for buildings up to 8-storeys high. Canadian Lift Slab construction started in Winnipeg in the early 1960's with Lount Construction Corporation founded by Graham Lount. The Canadian Lift Slab Corporation, a subsidiary of Lount Construction Corporation, has built up to 18 storey buildings and parking garages in Winnipeg, Toronto and Vancouver.

Lift slab construction exhibited considerable popularity throughout North America in the 1950's, 1960's and 1970's. The most recent Canadian project we are aware of is the Delta Mountain Inn Hotel in Whistler, British Columbia, built as part of a design/build contract by Texstar Construction Corporation of San Antonio, Texas in 1982.

The Lift slab construction industry in Canada declined after a number of collapses in the United States in the 1980's generally attributed to unsafe construction methods. The economic advantages of the introduction of the tower crane and fly form in construction also helped undercut lift slabs' economic advantage. Texstar Construction, however, continues to construct lift slab projects in the United States.

In Japan a modified system uses push-up construction, which provides better working conditions, especially during the monsoon season. This might be applicable in Vancouver region.

From an EcoSmart Concrete point-of-view, a lift slab construction offers some advantages over normal cast-in-place concrete which creates some very strong opportunities to re-institute the system in high-rise building construction.

Description

The Lift Slab System is a hybrid structural scheme comprised of cast on site post-tensioned concrete slabs supported on steel columns. The post-tensioned concrete slabs are cast on top of each other on the ground or podium floor with plastic sheets or an oil-based separator dividing them. The lowest level slab is cast first, with subsequent slabs poured directly on top of the preceding one. Steel shear heads are embedded within the slab around the columns to form an opening to facilitate the lifting process as well as a lifting attachment point and a welded connection point to the steel columns.

Some earlier projects have utilized normally reinforced concrete flat plates as well as beam and slab configurations. However, currently post-tensioned slabs are normally utilized for better lifting performance and also have the advantage of reduced concrete thickness. In Vancouver the slab thickness is usually 7½" due to mechanical ducts located within the slab. This could be reduced to 6½" for this particular project if the mechanical ducts are placed in a "bulk head" as commonly done in other parts of North America.

Before the lifting process commences all concrete slabs are tensioned at ground level, which eliminates the awkwardness of performing tensioning above-grade. The post tensioning increases the slabs spanning capabilities relative to thickness and thus can reduce the number of columns and, therefore, the number of jacking points. Furthermore, most of the concrete creep and shrinkage takes place on the ground and the restraint induced cracking of the floor slab is reduced.

After all slabs are poured at grade and cured, mechanical jacks mounted on steel castings that are supported on top of the steel columns lift the floor slabs at a rate of a few centimeters an hour sequentially into their respective positions. The steel columns are not extended more than 2-storeys above the slab that serves as a working platform to limit the unbraced length of columns and ensure temporary stability. The number of slabs lifted at one time varies between 2-5 depending on the jack capacity and floor configuration.

While the slabs are parked in temporary positions they are supported by wedges and tack welds to the steel columns. The lowest slab is parked in its final position and new sections of steel columns are spliced on top of existing columns (usually 2-storeys above working platform). The lifting process carries on while workers continue to work below finishing the permanent connections between columns and slabs.

Structural components such as cross bracing or shearwalls providing lateral stability for the building are installed at lower levels while lifting is proceeding above.

Advantages

- Because the slabs are poured on top of each other on the ground there is ample time available for curing high level SCM concrete, especially on the lower level slabs. The upper level slabs may require less SCM content, especially in cold weather to allow them to be lifted first without schedule delays.

- Since the slabs are poured one on top of the other, good quality curing of the concrete is guaranteed. Evaporation is less and the slabs maintain their warm temperature longer. This is especially critical in the good performance of SCM concretes.

- The post tensioned concrete slabs can be made thinner than normally reinforced cast in place systems, therefore, reducing material and cost. Additionally there are savings in foundations and lateral seismic design loads due to this reduced building weight. Thinner slabs also reduce the overall building height thus reducing cladding costs.

- Lift slab construction produces a flat slab soffit comparable to normal concrete flat plate construction. The concrete soffit can be spray finished to form the final ceiling surface.

- Lift slab construction eliminates slab shoring, formwork and craneage requirements. This results not only in reduced material usage but also in cost savings.

- Since the slab pours are not dependant on slabs reaching a minimum strength and a separate formwork removal and set up procedure, increased speed of construction is possible. This would be offset by the lifting operation but at worst there should be no negative schedule impact in utilizing lift slab construction.

- Concrete Creep and shrinkage induced cracks should be reduced as they occur at ground level before being restrained by the columns in their final location. Post-tensioning should also reduce slab cracking.

Disadvantages

- Lift slab construction is no longer a common building practice in the Vancouver area. We have been able to identify only one active contractor in North America, Texstar Construction Corporation of San Antonio, Texas performing lift slab construction. With so few contractors providing lift slab expertise, competitive bidding may not be possible.

- A 22-storey building is pushing the building height envelope for lift slab construction. We have been able to identify only 18 storeys as the highest building constructed with lift slab. The most economical building height seems to be in the order of 8 storeys.

- A number of collapses of buildings using the lift slab method in the 1970's gave lift slab construction a stigma of uncertainty. It appears, however, that these collapses occurred due to faulty construction practice and are not an inherent problem with the system itself. The structure is more inherently unstable during construction than normal construction, hence the designer and contractor must work more closely together to ensure safe construction practices.

- Lift slab works best with flat plates supported by steel columns, therefore, core walls and shear walls, or lateral cross bracing must be added as a separate operation after the slabs are in place..

- Steel columns and cross bracing require a separate fire-rated coating.

Environmental Performance

- Due to the longer possible curing times for the slabs before being post-tensioned and lifted, a high amount of SCM in the concrete mix is possible. The amount of SCM may need to be reduced for the upper slabs to ensure sequencing for the first lift.

- The concrete flat plate slabs can be made thinner than a comparable normally reinforced cast in place concrete flat plate scheme due to post tensioning, therefore, reducing the amount of concrete and cement required. Thinner slabs also reduce the mass of the overall building, resulting in reduced foundation sizes and design lateral seismic loads, which also leads to a reduction of concrete and cement used in the overall building.

- As all floor slabs are cast at ground level on top of one another no formwork and no shoring is required. This reduces waste produced on site and material used.

Cost

- Our initial findings indicated that a building constructed using the lift slab method can be built at competitive rates to conventional cast in place systems. At 22 storeys, however, the lift slab method may be less economical.

- No current comparative costs are available in the Vancouver market to compare lift slab with normal construction practices. It is interesting to note, however, that the 8 storey Whistler Delta Mountain Inn Hotel project constructed in 1982 was a design/build contract, so the procedure was obviously cost-effective in that market at that time.

- The savings on the eliminated formwork and shoring offset the costs for the mechanical jacks and steel casting. Furthermore, no tower crane is needed during construction.

- Due to the possible high SCM amount in the concrete mix and lesser material use the concrete cost could be reduced by an estimated 10%.

- The post tensioning components and expertise are readily available in the Vancouver market. The cost of post-tensioning is offset by reduced slab thickness.

- As the slabs are thinner than conventional cast in place slabs the material is reduced and the overall amount of concrete used which results in lower costs.

- Thinner slabs also reduce the overall building weight, which reduces the foundation and lateral load element size and material and labour costs.

(b) <u>Post-Tensioned Concrete Construction</u>

Read Jones Christoffersen Ltd. also investigated the possibility of using cast-in-place post-tensioned concrete flat plate construction in lieu of normally reinforced concrete construction for the typical floors of this building. Our initial review indicated that there is some possibility of maximizing the use of SCM concrete in these slabs, though we did not pursue this to the same degree as we did with the lift slab construction technique.

It appears possible, from our initial investigation, to utilize a high cement content concrete with a faster setting time at the perimeter of the typical floor slabs where the post-tensioned anchors are located and using a lower cement content with a higher SCM in the interior portion of the slab where initial concrete strength is not as quickly required. The higher early strength concrete mix is required at the perimeter to deal with the high stress concentration generated at the post-tensioning anchors.

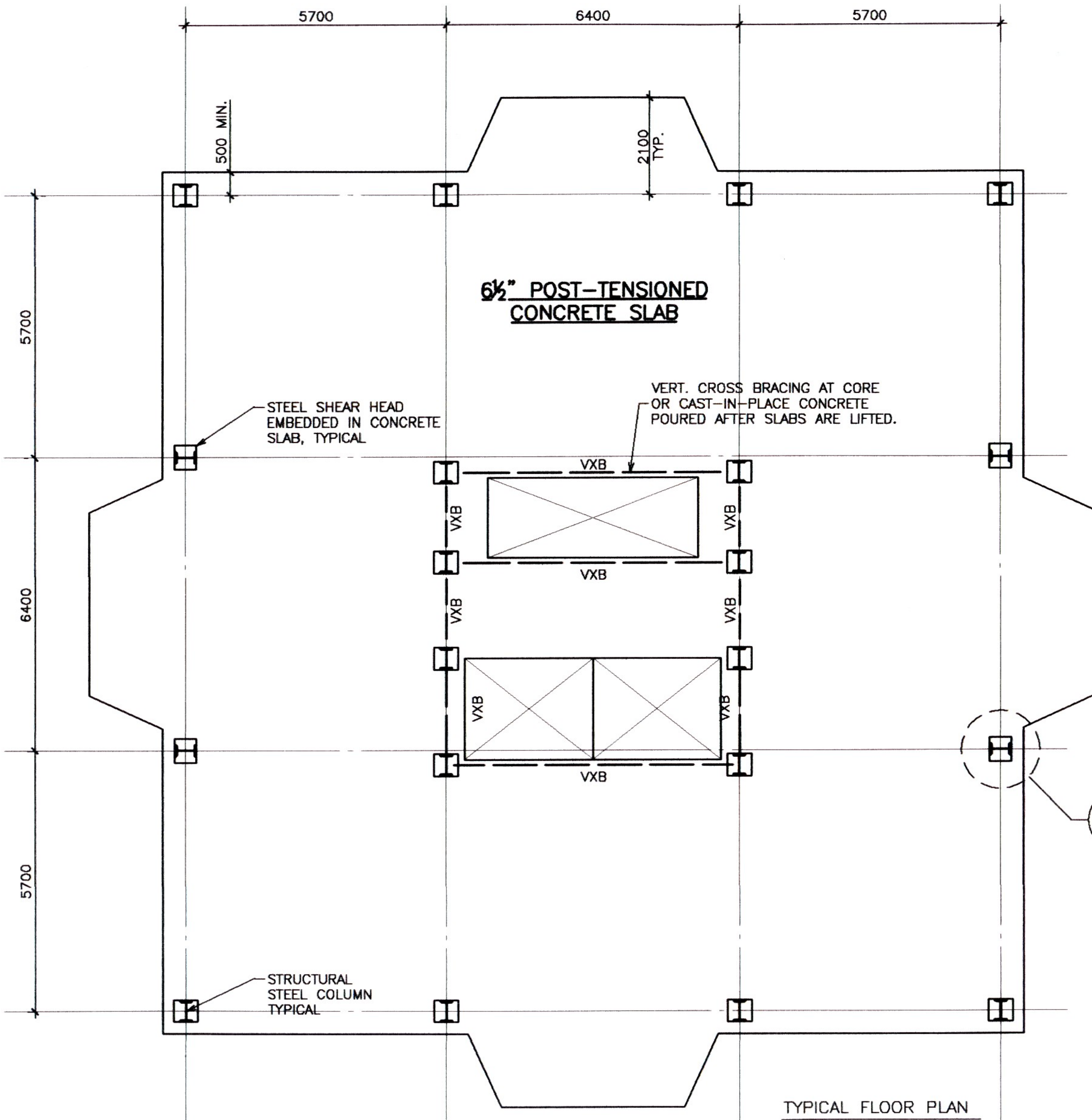
This would allow the tensioning of the slab at a relatively earlier age where the high stress at the anchor locations could be accommodated by the higher early strength perimeter concrete and the slower setting SCM concrete in the middle could be supported by the initial post-tensioning thus eliminating the loss in curing time at a lower compressive strength than required by normally reinforced concrete.

This method of construction would be very similar to the traditional method of high-rise flat plate construction in the Vancouver market utilizing fly forms and power crane construction. The use of post-tensioning construction would result in thinner slabs than traditional concrete with the resulting savings in material, cement content, and reduce building weight also resulting in reduced footing sizes and lateral load requirements.

However, a more detailed study of this method would be required to determine exactly the stress levels required to support the slabs at an early stage to allow removal of the formwork without delaying construction. There is also concern with respect to the minimum shear strength required at column locations to support the slab, though this could also be achieved by using higher early strength concrete at these locations as with the perimeter.

The disadvantage of this system is that two different concrete mixes would be utilized for the floor resulting in greater complication in the construction and potential for error.

There is also concern that the additional cost of the post-tensioning would not be offset the savings achieved by the thinner slabs and the SCM concrete used, especially if the minimum slab thickness is restricted to 7 ½" to allow in slab placement of the mechanical ducts as is common practice in the Vancouver market.



TYPICAL FLOOR PLAN
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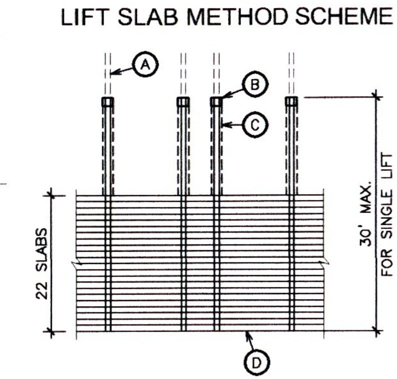

- (A) NEW STEEL COLUMN TO BE SPLICED ON TOP.
- (B) MECHANICAL JACKS FOR SLAB LIFTING
- (C) LIFTING SCREW
- (D) CONCRETE SLABS CAST ON GROUND FLOOR AND LIFTED INTO THEIR RESPECTIVE POSITIONS.

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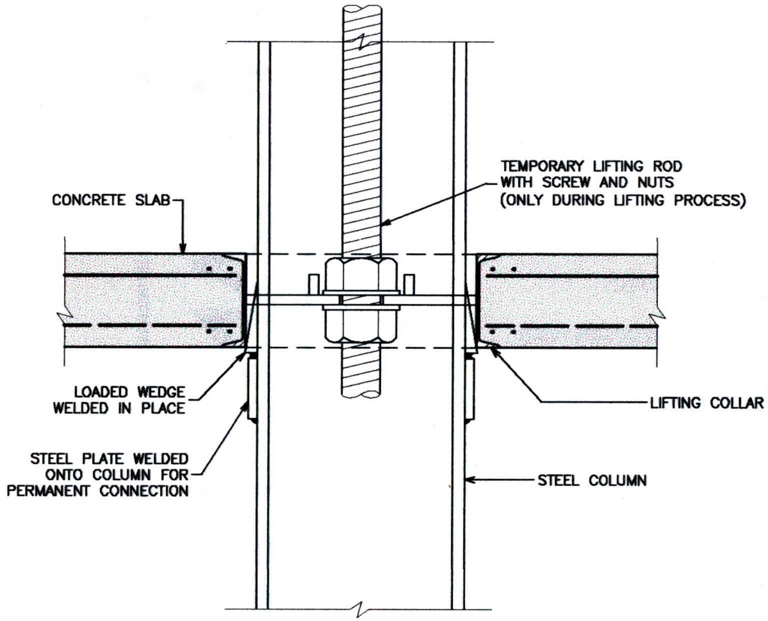
ECOSMART
High - Rise
Early Design Study

LIFT SLAB SYSTEM FLOOR PLAN

RJC 38647.01
SEPT. 25, 03
SCALE AS NOTED



2 ELEVATION
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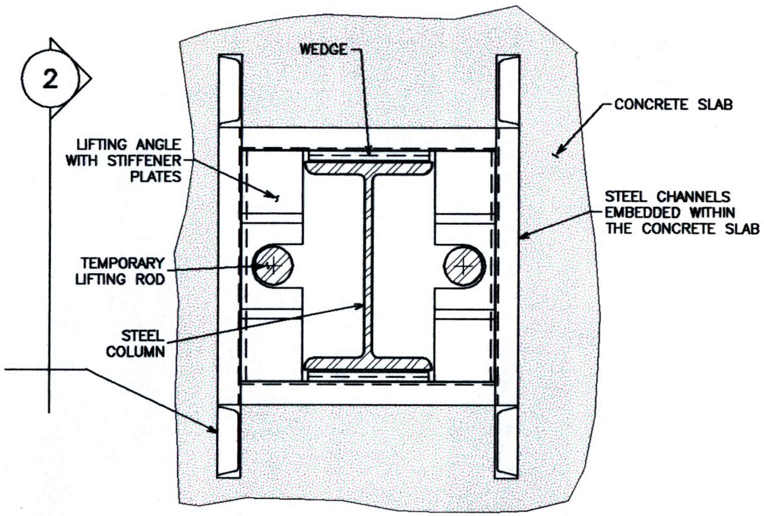

PLAN

1 TYPICAL EMBEDDED SHEAR HEAD/ LIFTING COLLAR WITH LIFTING RODS
1 : 10

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LIFT SLAB SYSTEM SECTIONS

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3.2 PRECAST CONCRETE

(a) Hybrid Concrete and Precast/Cast-in-Place Concrete Hybrids

History

Hybrid precast/cast-in-place concrete floor systems have been utilized extensively throughout North America for many years. The most common systems utilize precast/prestressed concrete double-tees or hollow core slabs with 2 or 3 inch thick cast-in-place concrete toppings.

The system we are reviewing in this report, however, is more aggressive than these typical systems in its greater use of field poured cast-in-place concrete. The precast concrete elements are the minimum thickness required to form, ship and erect and to act as permanent formwork for a thicker cast-in-place topping. This is similar to a system used on a design/build parking structure in Winnipeg in the mid 1990's for which Read Jones Christoffersen were the structural consultants.

Description

This hybrid composite system consists of precast/prestressed concrete elements that are shop manufactured combined with field cast concrete topping. The precast elements in this example consist of inverted channel elements for the typical slab portions which are supported on precast concrete 'U' shaped beam forms. Column forms can also be similarly fabricated. The precast forms could be cast in a certified precast concrete plant with as much SCM's as possible or they could be field cast on site, depending on site configuration and weather. Our initial findings indicate an SCM range of 20%-25% is possible. These forms need to reach sufficient strength to be lifted out of the mould after 24 hours in order to maintain an economical viable production cycle for a precast plant. This time constraint governs the SCM content.

The precast column and beam forms are shipped to site and erected and temporarily shored and secured by steel clamps. The floor channels are placed onto the precast concrete beam forms and additional steel reinforcement is placed and tied. A high SCM content concrete mix is then field poured into the beam and column forms, as well as the channel forms to finish the floor slab. The shores are left in place until the field cast concrete has reached sufficient strength. Temporary shoring could be reduced if the precast panels were designed to span further under the weight of wet concrete. This would produce thicker precast elements, however, resulting in greater shipment costs and reduced use of field cast high SCM concrete. An economical balance also has to be established between shoring cost and floor thickness. The use of temporary shoring allows reduced total floor thicknesses and reduced precast concrete thickness.

The lateral system of the building could be either a conventional cast-in-place core or a precast core utilizing the findings of the PRESSS research. This core could be made up of shear walls with vertical post-tensioning.

Advantages

- The precast concrete is fabricated in a heated controlled environment so that the SCM concrete can be maximized for that environment to meet the timing requirement to maximize casting bed utilization. It is estimated that 25% SCM concrete use is possible year around.

- It is estimated that the amount of field poured concrete in the slabs would be approximately 40% of the total slab concrete. This concrete can maximize the amount of SCM's as it is not dependent on an early strength gain to allow quick form removal.

- This system eliminates the need for separate slab formwork. Therefore the additional cure time for SCM concrete does not affect the floor construction schedule as the precast concrete forms are part of the permanent floor system and do not need to be removed. In addition, the floors that are poured are readily available for other trades to continue work as soon as concrete initially sets.

- The slab soffit finishes can be controlled within the plant environment, resulting in a better quality. Therefore, concrete can be exposed and the need for additional finishes is reduced.

- The thermal mass of the concrete in this system is comparable to a normal cast in place concrete slab.

- All technology and expertise is readily available in most urban areas and competitive tendering can be achieved.

- Any mechanical ducts or radiant floor heating can be placed in the deeper part of the channel form.

Disadvantages

- The tolerances between the structural elements do not allow much room for error or damage on site. This forces the contractor to monitor quality to a higher degree, which could result in higher costs.

- Precast concrete elements must have a high level of repetitiveness and a minimum number of different element types to remain cost effective. This places a level of dimensional and architectural constraint on the layout of the floor slab to a much greater degree than normal cast in place concrete.

- This system requires a drop beam configuration at the perimeter and internally to support the slab panels. This creates an uneven ceiling line.

- There are a limited number of precast concrete contractors in any one area. This could result in less competitive bidding than other structural systems.

- The construction schedule on site becomes heavily controlled by the ability of the precast concrete supplier being able to maintain a consistent and timely delivery schedule to the site.

Environmental Performance

- The amount of concrete is approximately the same as in a similar cast in place system, however the amount of SCM can be significantly increased primarily in the topping, which comprises at least 40% of the total slab concrete. Even in the remaining 60% of the slab concrete made up of the precast concrete elements, the controlled fabrication environment would allow a consistent use of 25% SCM regardless of the outside temperature.

- Slab formwork is eliminated, hence reducing the amount of waste and labour and removing the element from the critical path.

- As all the concrete can be exposed, this system lends itself ideally for the use of its thermal mass and radiant floor heating. A variation could be to use the radiant floor heating pipes during construction by pumping hot water through and therefore speeding up the curing process. One would be in control of the slab temperature and could optimize the concrete mix (amount of fly- ash or slag) with the temperature.

- The thermal mass of this system is comparable to normal cast in place concrete construction and could be utilized in reducing heating and cooling costs.

Cost

- Precast concrete fabricators contacted in this study indicate that the precast elements can be produced at competitive rates if the shapes are kept relatively simple e.g. channel or U- shape and the concrete mix allows a 24 hour turn around time for the forms.

- In order to keep the number of forms to a minimum, the floor elements should be standardized and the number of repetitive elements should justify the production.

- Formwork such as fly forms or free forming is not necessary, hence a reduction in cost, however this reduction would be offset by costs of precast production and erection.

- The precast columns and beams can be exposed as precast quality can be controlled closely. This reduces the cost of any additional finishes required.

- The concrete topping mix should be approximately 10% cheaper than the standard concrete mix with no SCM's.

(b) PRESSS

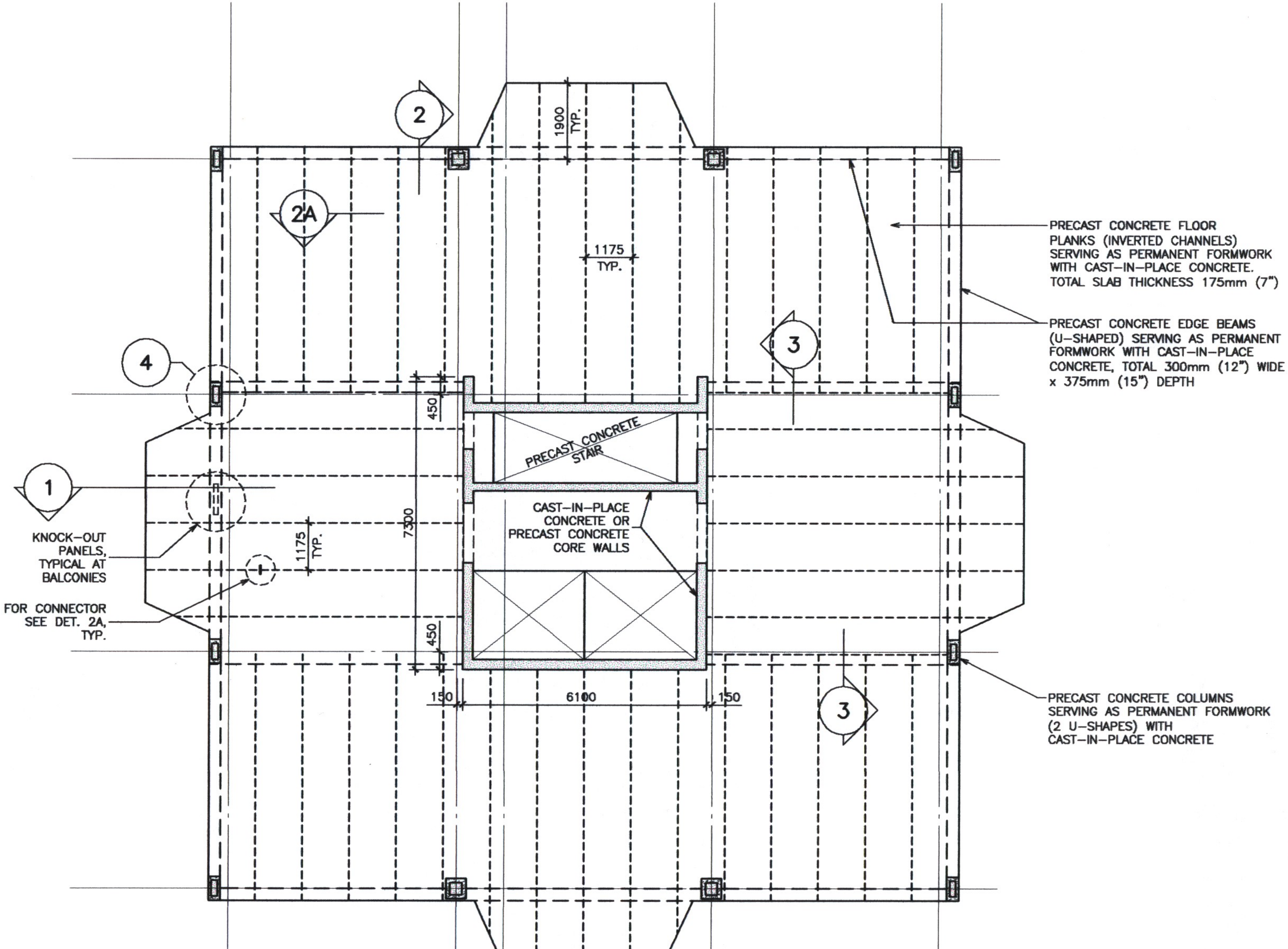
PRESSS (Precast Seismic Structural Systems) was specifically addressed in the EcoSmart study terms of reference. We have, therefore, specifically reviewed this system in terms of its application to the reduction of cement usage in high-rise residential construction.

It appears that PRESSS is somewhat a misnomer in that it is not actually a new or different structural "system". PRESSS appears to be a method of utilizing precast concrete structural elements in the lateral load-resisting systems of buildings in seismic areas to produce a ductile load-resisting system able to absorb large displacements and return to its preloaded shape after the earthquake. It appears to be a promising initiative by the precast concrete industry to make their product serviceable in seismic areas.

Its focus is primarily on the detailing of connections in moment resistant frames to allow them to absorb seismic energy and large flexural movements and return to their original configuration. Precast concrete shearwalls have also been detailed to perform in a similar manner.

PRESSS itself does not address the focus of this study, which is to reduce the use of cement in high-rise residential construction by increased use of SCM's. PRESSS allows, and possibly encourages, the use of precast concrete construction in seismic load areas, but unless the use of precast concrete itself can accomplish the EcoSmart objectives, there is little value with respect to SCM usage in utilizing PRESSS or precast.

As discussed in section 3.2 (a) above, the use of SCM's in precast concrete structural elements is limited by the relatively short turn around time (24 hours) required by the precast plants. Longer cure times would require more forms and greater floor space resulting in greater costs. It appears that even in the controlled heated environment of the precast plant, an SCM content in the order of 25% is the most that can be achieved. This is comparable to normal cast in place concrete construction in good weather. It will perform better than cast in place concrete only in cold weather. However, precast/prestressed structural elements will be more efficient in the use of materials than cast in place concrete, which will be of some benefit in reducing total material and therefore cement content, but the relatively short spans of the study floor plate does not fully utilize the increased spanning capabilities of prestressed/precast concrete structural elements other than hollow core panels. Hollow core panels, which use a "dry cast" extruded technology in their fabrication, cannot utilize larger volume of SCM's in their production.



TYPICAL FLOOR PLAN
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HYBRID PRECAST SYSTEM FLOOR PLAN

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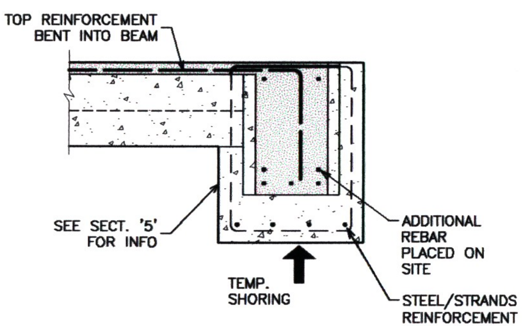

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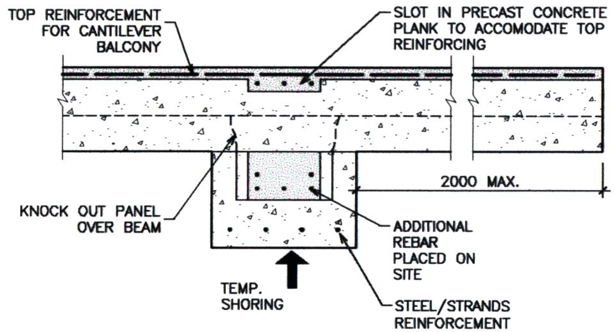

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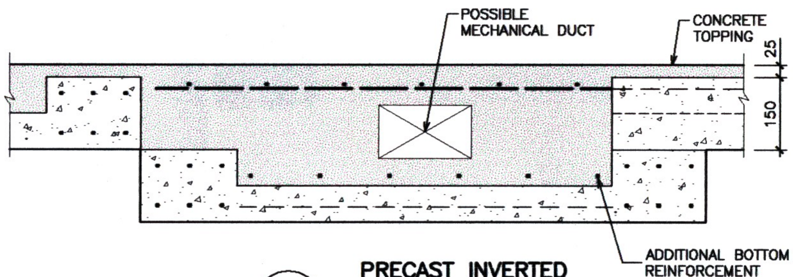

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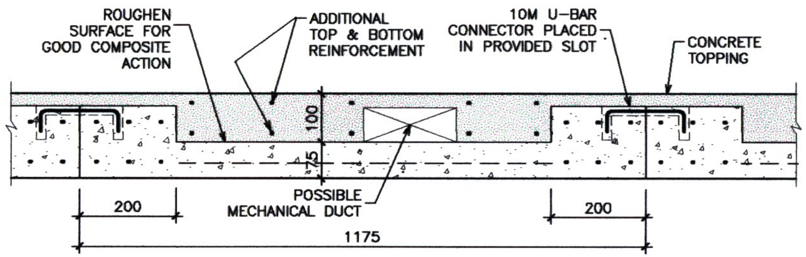

2A PRECAST INVERTED CHANNEL SECTION
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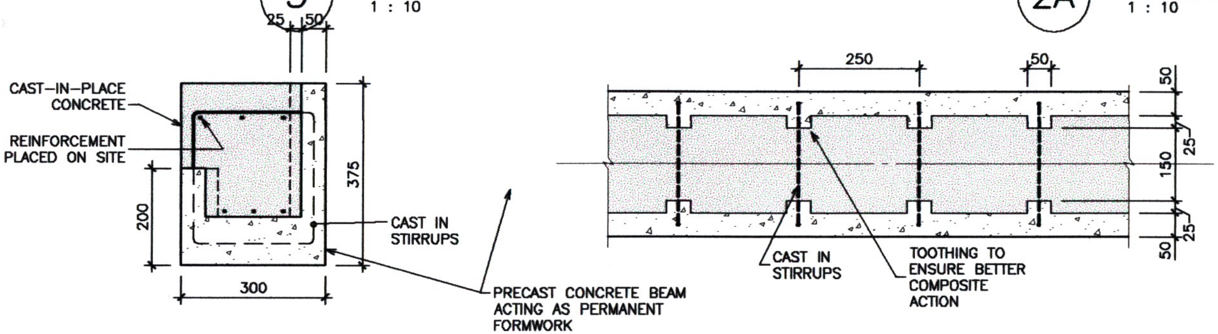

5 TYPICAL BEAM BUILD UP
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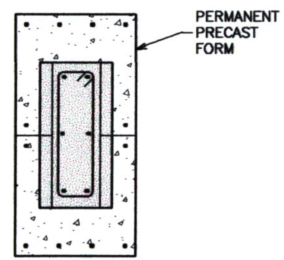

4 TYPICAL COLUMN
1 : 10

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ECOSMART
High - Rise
Early Design Study

HYBRID PRECAST SYSTEM SECTIONS

RJC 38647.01
SEPT. 25, 03
SCALE AS NOTED

3.3 HYBRID STEEL AND CONCRETE SYSTEMS

(a) Hambro Joist System

History

The Hambro System is a proprietary floor framing system originating in Canada that has been used in residential construction across North America for more than 30 years. The Hambro composite floor joist system was invented and patented by three engineers, one from Canada and two from Great Britain during the 1960's. The name Hambro evolved by taking a portion of the name of each of the three engineers. By 1970, the Canam Menac Group joint-ventured with Hambro to manufacture the joists and ultimately bought the patent in 1980.

Description

The Hambro System is a hybrid concrete/steel structure that relies on composite action between steel joists and a concrete slab. The composite action is achieved by a z-shaped joist top chord, which is embedded into a relatively thin cast in place concrete slab. Thus the concrete takes compression forces and the steel bottom chord takes the tension forces of the bending stresses of the floor system.

The Hambro floor joists are supported by steel beams or load-bearing walls at bearing lines, structural steel columns, and either a cast-in-place concrete core or a braced structural steel core. The use of a steel plate shear wall system could be considered for the core as well. The structural steel frame is erected as a conventional open web joist steel structure. Once the Hambro joists are placed, specially fabricated "rollbars" are placed perpendicular to the joists into slotted holes in the top chord. The rollbars support 4' x 8' plywood formwork for the concrete deck. The 4-foot joist spacing is dictated by the standard dimension of plywood. Steel welded wire mesh is then placed on the formwork and a 25 MPa concrete deck with up to 35% SCM is placed. The concrete slab spans the 4 feet between the Hambro joists.

The plywood forms can be stripped after 48 to 72 hours or once 4 MPa strength is reached. Another alternative is to have two sets of plywood forms, which allows longer curing and therefore a higher amount of SCM's.

The composite floor system for the slab spans of this project are comprised of a 3¼" thick concrete slab and 10" deep Hambro steel floor joists.

A tapered cast in place concrete cantilevered slab tied back to a supporting steel torsion tube forms the balconies. The balcony slabs would be formed and shored as per conventional concrete construction. They could either be cast with high cement content concrete to allow early stripping or could utilize high SCM concrete if this small amount of formwork can be doubled up and left in place longer to allow for the slower cure time of the SCM concrete.

A UCL 2-hour fire-rating is achieved by an assembly of the 3¼" concrete slab with wire mesh reinforcing, unprotected steel joists, and ½" gypsum board ceiling on furring channels attached directly to the joist bottom chords.

Tests performed by the manufacturer show a sound rating of 57 STC for the selected assembly, which exceed the design brief requirement of 52 STC.

All air ducts and other mechanical ducts or equipment can run in the ceiling space between and through the joists. For 10" deep joist a maximum duct size of 6"diameter or 5"x 5" square or 7"x 4" rectangle is possible through the joist diagonals.

Advantages

- The system is readily available in Canada and the US and has a proven track record in high-rise construction.
- The speed of erection is increased due to the prefabricated steel elements, which reduces the construction period and overall cost of the project.
- The formwork is comprised of regular 4 feet wide plywood panels that correspond with standard plywood dimensions. Therefore the labor costs and material waste are reduced.
- The amount of concrete is roughly 50% of a normal cast in place concrete floor slab system and SCM content can be increased, as only 4 MPa is needed to be reached before stripping of plywood forms.
- The Hambro floor system is a relatively lightweight structure resulting in reduced foundation loads and sizes and reduced design seismic lateral loads. This reduces both the amount of material required in the building structure and its cost.
- The necessity of bulkheads is minimized as most of the mechanical ductwork can run in the ceiling space.

Disadvantages

- Because the Hambro system is a proprietary product, competitive pricing is not available. A negotiated price must be determined before design and tendering other components of the building occur.

- A separate drywall ceiling element is required below the structural system to achieve a ceiling finish and a fire rating. This leads to additional cost and construction complexity.

- Fire rated dampers are required where mechanical systems penetrate the fire rated ceiling assembly

- Because of its light weight, the Hambro floor system is more susceptible to noticeable floor vibrations than thicker concrete slabs. Therefore greater design care is required which may affect slab thickness and joist depth described above.

- The Hambro floor system is a deeper assembly than a comparable concrete slab. This will result in a taller building with increased cladding costs due to increased building height.

- The Hambro system does not lend itself to typical cantilevered balcony construction. A separate cast in place cantilevered balcony slab is required.

- The system is based on a 4 feet wide joist spacing module to maximize plywood efficiency. Floor plates that do not suit this module will be more complex.

Environmental Performance

- The amount of concrete is reduced compared to normal concrete slab construction, therefore CO_2 emissions are reduced.

- Most of the structural steel used is 100% recycled and the steel elements are 100% recyclable after the building is demolished.

- The amount of SCM's in the concrete mix can be increased over normal cast in place concrete construction.

- Forms can be stripped when the concrete has reached 4 MPa strength as opposed to 17 MPa for normal concrete slabs.

- Due to standardization of the dimensions to suit industry standards the amount of on site waste and cutting (plywood comes in 8-foot sheets) is minimized, hence reducing also cost.

- The steel rollbars for formwork support are reused on other sites, therefore not creating additional waste.

- The drywall components forming the ceiling are not desirable from an environmental point of view as they are not recyclable.

- The thermal mass of the building is less than a comparable cast in place building, increasing cooling and heating costs.

- The gypsum board and furring channels required for the ceiling results in an increased embodied energy used for the production of these elements.

Cost

- The 3¼" thick slab is roughly 50% thinner than a comparable cast in place concrete slab. Therefore savings are realized in reducing material (concrete and reinforcement) and labour costs.

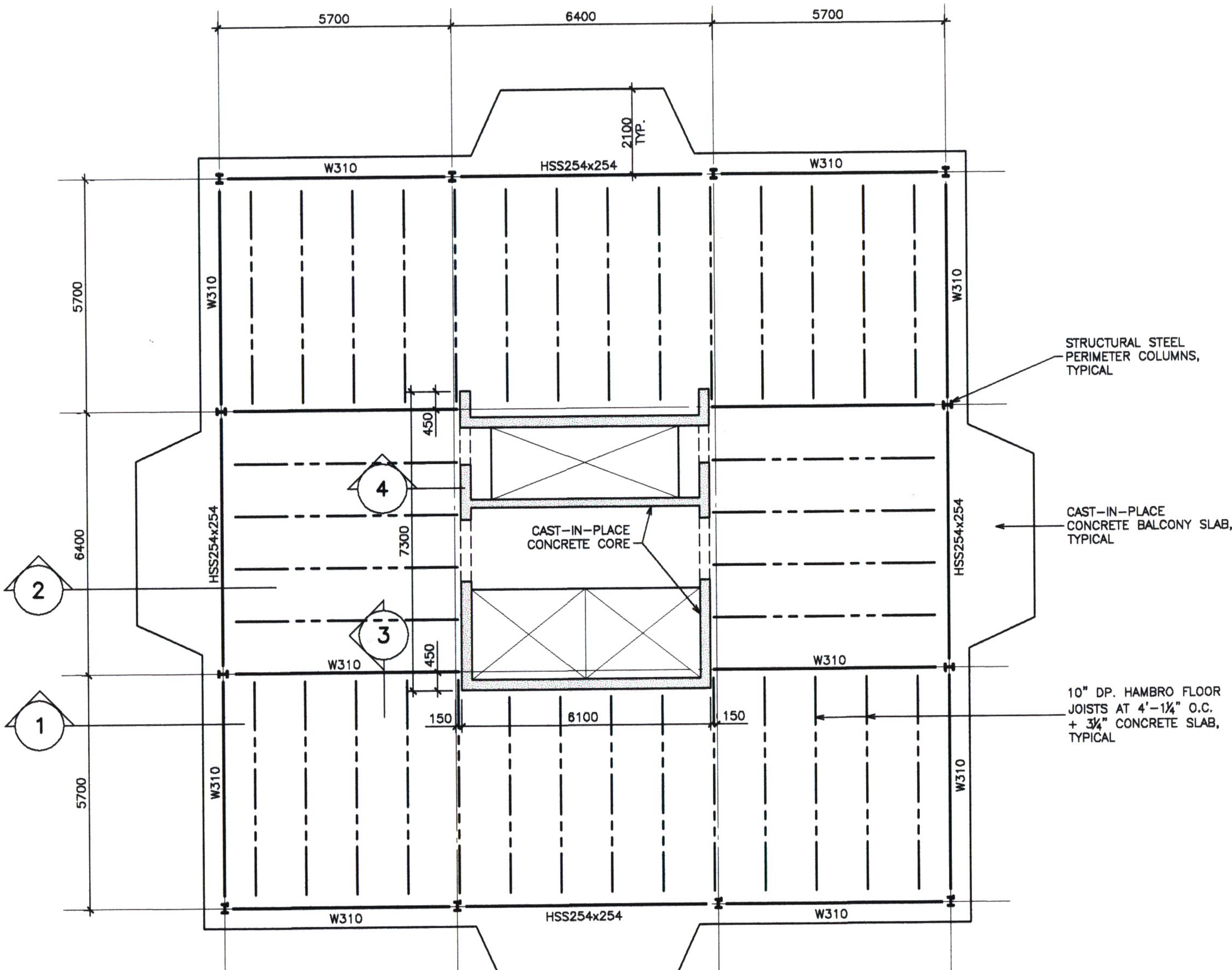
- The Hambro system eliminates normal fly form construction costs.

- The overall building becomes lighter, hence reducing foundation sizes and lateral load elements.

- The speed of construction on site is increased as joists and steel elements are fabricated off site.

- There would be increased cladding cost due to the increased building height that results from the increased floor depth.

- The drywall ceiling, which is required for the fireproofing presents an additional cost.



TYPICAL FLOOR PLAN
SCALE 1:100

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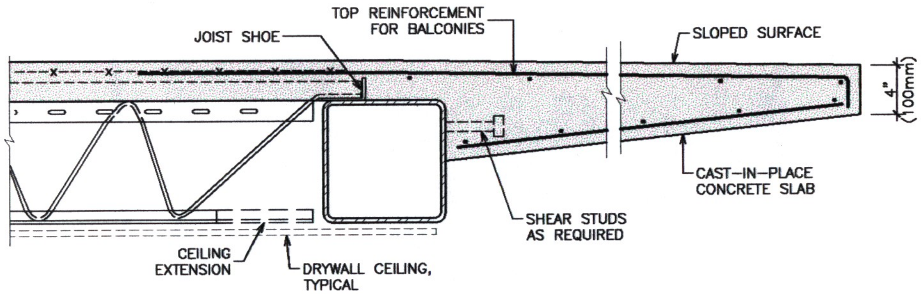

2 BALCONY DETAIL
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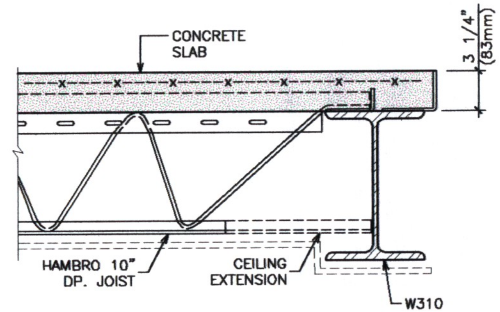
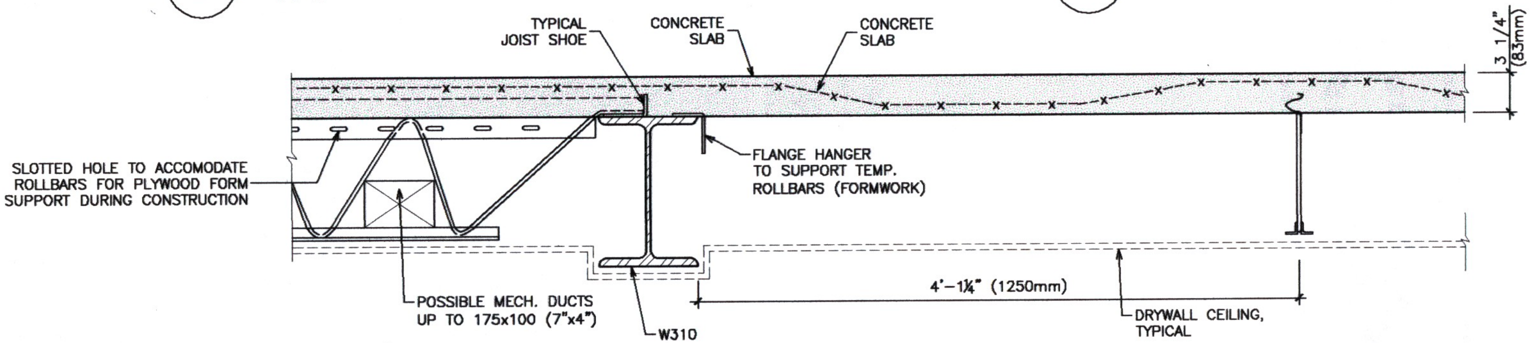
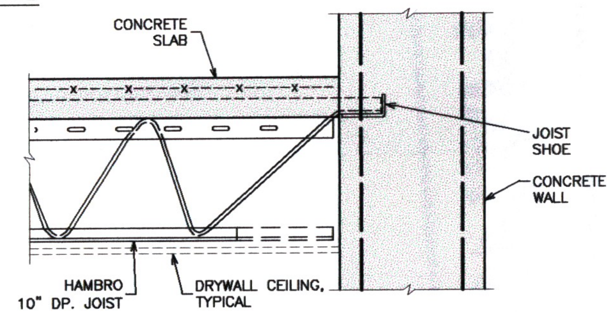


1 TYPICAL EDGE CONDITION
1 : 10



3 TYPICAL INTERIOR DETAIL
1 : 10



4
1 : 10

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4.0 ADDITIONAL CONCEPT FOR CURING IMPROVEMENT OF HIGH SCM CONTENT MIXES

Another approach that would improve the use of SCM's is to combine radiant floor heating with slab temperature control during the curing period. This concept is based on the principle of using the plastic pipes that are embedded in the slab during concrete curing by temporarily pumping hot water through them. Therefore, the concrete temperature is increased and the curing time is substantially reduced. This is similar to current practices where preheated water for concrete mixes is employed for cold weather placement. The temperature could be controlled very closely and could go as high as 70 degrees Celsius before the concrete curing would be adversely affected. However, this concept requires coordination and evaluation with the permanent heating system requirements for the building.

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APPENDIX A

COMPARISON OF CONCRETE VOLUMES

Comparison of Concrete Volumes

SYSTEM		Area m^2	Lift Slab concrete volume in m^3		Precast Hybrid concrete volume in m^3		Hambro concrete volume in m^3
Typical floor							
	floor	353.4	58.3		61.8		29.2
	balconies	30.7	5.1		5.4		2.5
	openings	-20.2	-3.3		-3.5		-1.7
	Total	364.0	60.1		63.7		30.0
Columns		steel columns		8 col. @ 400mm x 540mm	4.1	steel columns	
				4 col @ 500mm x 500mm	2.4		
				Height 2400mm			
Core Walls		59.28	steel	average 400mm thick	23.7	average 350mm thick	20.7
Total volume per floor			60.1		94.0		50.8
Total volume for 22 storeys			1322.0		2066.9		1117.4
ignoring podium slab etc			add steel columns and core		no additional steel		add steel columns and Hambro joists