Editorial Manager(tm) for Structural Concrete
Manuscript Draft

Manuscript Number:

Title: Belgrade's DELTA CITY shopping mall - design and construction

Article Type: Technical paper

Corresponding Author: Associate professor Snezana B Marinkovic, Ph.D

Corresponding Author's Institution: University of Belgrade, Faculty of Civil Engineering

First Author: Snezana B Marinkovic, Ph.D

Order of Authors: Snezana B Marinkovic, Ph.D; Veljko M Kokovic, MSc.; Ivan S Ignjatovic, MSc.; Vanja H Alendar, MSc.

Abstract: The structure of DELTA CITY shopping mall in Belgrade consists of two separated structures: the structure of the mall and the structure of the multi-story open garage. The overall dimensions of the irregular layout of the structure are 210 m x 120 m, with four main levels in the mall and five parking levels in the garage. Because of the different exposure conditions, the structure of the garage is separated from the mall's structure with an expansion joint at all the levels, except at the level of the foundation slab.
The mall's framed structure is designed without any expansion joints, except for temporary joints during the construction stage. It consists mainly of reinforced concrete cantilevered columns cast in place, at typical spans of 8.2 m x 8.2 m, precast reinforced concrete simple beams and precast prestressed hollow core slabs. The reinforced concrete frames cast in place are designed mostly at the façade, to provide additional seismic resistance and to control lateral deflections. The main structure of the open multi-story garage consists of reinforced concrete frames cast in place and precast hollow core slabs and it is designed for exposure class XD3, with special attention paying to durability requirements.
Due to mainly precast structure, especially hollow core slabs as a floor solution, the complete concrete structure of approximately 80000 m2 was constructed for less then 12 months.

- Date written: 28-03-2009.
- Title: Belgrade's DELTA CITY shopping mall - design and construction
- Authors:
Snežana B. Marinković*, PhD.
Associate Professor, Faculty of Civil Engineering, University of Belgrade, 11000 Belgrade, Serbia
Veljko M. Koković, MSc.
Assistant, Faculty of Civil Engineering, University of Belgrade, 11000 Belgrade, Serbia
Ivan S. Ignjatović, MSc.
Assistant, Faculty of Civil Engineering, University of Belgrade, 11000 Belgrade, Serbia
Vanja H. Alendar, MSc.
Technical Director, DN Engineering Consultants, 11000 Belgrade, Serbia

- *Corresponding author:
Snežana B. Marinković
Faculty of Civil Engineering
University of Belgrade
Bul. kralja Aleksandra 73
11000 Belgrade, Serbia
e-mail: sneska@imk.grf.bg.ac.yu
Tel: + 381 11 3370 102
Fax: + 381 11 3370 223

- Number of words: 4042
- Number of figures: 20
- Three key words: precast concrete structure, hollow core slabs, durability

Abstract

The structure of DELTA CITY shopping mall in Belgrade consists of two separated structures: the structure of the mall and the structure of the multi-story open garage. The overall dimensions of the irregular layout of the structure are 210 m x 120 m, with four main levels in the mall and five parking levels in the garage. Because of the different exposure conditions, the structure of the garage is separated from the mall's structure with an expansion joint at all the levels, except at the level of the foundation slab.

The mall's framed structure is designed without any expansion joints, except for temporary joints during the construction stage. It consists mainly of reinforced concrete cantilevered columns cast in place, at typical spans of 8.2 m x 8.2 m, precast reinforced concrete simple beams and precast prestressed hollow core slabs. The reinforced concrete frames cast in place are designed mostly at the façade, to provide additional seismic resistance and to control lateral deflections. The main structure of the open multi-story garage consists of reinforced concrete frames cast in place and precast hollow core slabs and it is designed for exposure class XD3, with special attention paying to durability requirements.

Due to mainly precast structure, especially hollow core slabs as a floor solution, the complete concrete structure of approximately 80000 m^2 was constructed for less then 12 months.

Introduction

DELTA CITY shopping mall located in Belgrade is the first building of the "shopping mall" type in Serbia, Figure 1. The Investors were companies Delta M d.o.o. and Delta City d.o.o from Belgrade. The authors of this paper were engaged with preliminary and main structural design.

The whole building is in plan functionally devided into two blocks: shopping mall and multi-story open garage, Figure 2. The overall dimensions of the layout of the structure are 210 m × 120 m. Area in plan is around 20.000 m^2, while the total gross area is approximately 80.000 m^2, with four main levels in the mall (underground garage, ground floor, first and second floor with multiplex cinema), Figure 3, and five parking levels in the open garage. The storey height is 5.80 m in mall i.e. half of it, 2.90 m in open garage. The common continuous foundation slab is positioned at 5.1 m below the level of the surrounding landscape terrain. The highest expected underground water-table is about 1.0 m below terrain.

Due to uneven floor height, structure mass and stiffness of the mall and the open garage, as well as different exposure conditions during service life, garage structure is separated from the mall structure by vertical expansion joint 20 cm wide along the entire structure height, except at the foundation level.

Shopping mall structure

Building description

In general, the building is organized at orthogonal grid at spacing of 8.2 m in both directions. Due to irregular shape of the layout, this grid is inevitable disturbed around the perimeter. Three main atriums (A-C) and curved pedestrian passages additionally impair the simplicity of the layout, as well as in-plane stiffness of the slabs, Figure 4. At ground level, the curved colonnade of columns turns into the orthogonal column layout in the underground garage, by means of heavy cast in place transfer structure.

Above the ground level, three cascaded floor slabs rise from east to west, ending with the highest part of the building - six cinema halls at north-west side of the building, Figure 1. The cinema is a steel structure, with each of halls completely isolated against vibrations by means of "Sylomer" pads.

Asymmetric floors are supported by grid of columns of constant cross-section 60 cm x 80 cm in the underground garage, 60 cm x 60 cm above ground level and 40 cm x 60 cm in façade along with stair-shafts (ST) mainly positioned close to the perimeter of the building, Figure 4. The height of the columns above the ground level is 11.6 m - 17.4 m.

Perimeter retaining 40 cm thick wall together with foundation slab and slab at ground level acts as a stiff base box, providing the horizontal supports to cantilevered columns.

The structure is designed for XC1 exposure class and 90 min fire resistance.

Construction and structure concept

From the very beginning, the RC/PT hybrid structural concept of precast floors and cast in place columns/stair-shafts was adopted as an optimal solution which should provide cheep and fast construction, and later on easy maintenance.

Two options of construction sequences were analyzed: upward floor-by-floor progress-ing, with cranes positioned at the perimeter and inside the building, and, frame-by-frame of complete height methodology, moving from west to east. The former solution was finally adopted by Contractor.

Dealing for the first time with such a large layout, the permanent expansion joint across the middle of the mall building was suggested, with two blocks of about 100 m in length. However, appreciating Architects' vast world-wide experience, the structure was finally designed without permanent expansion joints. To compensate for thermal movements during bare structure construction, structure above foundation was temporarily divided in three free blocks, with expansion joints to be closed after closing of building envelope, Figures 5-6. Ground floor slab of somewhat larger eastern block was temporarily horizontally disconnected from the perimeter retaining wall as well, wherever it was possible.

Spatial frame concept

Due to, for temperature effects unfavorable position of stair-shafts along perimeter of the building, as well as questionable transfer of wind/seismic forces from patchwork of floor slabs to stair-shafts with low axial loading, the spatial frame concept of the structure was adopted, without shear walls or bracings. All façade elements and partitions made at large from "Ytong" blocks were designed to accommodate for building thermal movements.

The stairs and lift-shafts were designed as less stiff framed towers with precast flights, although wall-box concept with slab expansion joint around the core was also possible solution. Together with about 250 cantilevered columns with height/width ratio of about 20, those medium-ductile vertical elements were capable to provide enough load capacity in the case of 475 year return period earthquake, with low ground acceleration of 12% of gravity, but horizontal displacements were excessive yet.

For displacement control, the full moment resisting frames, with beams cast in place as well were introduced. The basic so-called "seismic frames" were positioned in plane of external/internal façade frames, to increase building torsional stiffness, as well as to avoid local torsion problems due to eccentric connection of precast slabs and façade beams, Figure 7. In course of structure stiffness optimization, few transverse frames were added to the west side, where the concentration of building mass was more pronounced.

In preliminary design stage, a full-precast concept of seismic frames was examined as well. The advantage of cast in place columns was that it was easy to provide continuation of precast simple beams by adding as much as needed upper reinforcement over columns – for additional gravity loads precast beams could act as continuous beams. If, for the earthquake load the sign of the resulting support bending moments is changed, lack of lower reinforcement continuity will result in potential beam plastic hinges developed on only one side of the span – not usual, but might be useful enough. However, being positioned mainly in façade with narrow columns and façade eccentrically loaded beams susceptible to torsion as well, the cast in place moment resisting frame concept was finally adopted.

Floor structure

The 80 cm thick floor structure comprises:

- precast and semi-precast (temporarily propped) RC beams in longitudinal – east-west direction, supported by column corbels through steel leveling pads and 25 mm thick layer of non-shrinking mortar, Figures 8-9;
- prestressed hollow-core slabs (HCS) of 20-35 cm in depth, supported through EPDM strip by lateral continuous beam corbels. At beam ends, lateral corbels were

designed in form of fork, to provide HCS support over the width of the column and lateral formwork for column at the same time, Figure 8;

- RC topping of 7.5 cm in depth with wire fabric;
- transversal in-plane stiffening RC ties in line of every second-third column with depth equal to adjacent HCS depth, which together with HCS, edge beams and topping create in plane stiff floor diaphragm.

Where precast concept wasn't applicable, the RC cast in place structures were applied, Figure 4.

Introduction of seismic moment resisting frames allowed all other, the majority of beams to be designed as RC precast simple beams, with minimum upper axial continuation reinforcement – 2ϕ25 bars, passing through the columns cast in place. At preliminary stage, all beams were designed as precast prestressed elements but, when later on storey height was increased, the RC concept was adopted to enable local precast contractors to bid too.

Connection of precast HCS and cast in place narrow façade beams – seismic frames was initially designed as so-called "indirect support" detail, with temporary props, Figures 10-11. The main reason was to eliminate the beam corbels and to produce monolithic connections that might resist torsion. Without any previous experience with such connection details, some literature/practice research was conducted and the *fib* Bulletin 6[1] was used as a reference document. Precast contractors engaged in this project didn't have such an experience as well, but they were ready to accept designers solution if experiments validated it.

Domestic law claims that new technologies should be verified by testing, so experiments were organized at IMS Institute in Belgrade according to program prepared by designers, with full support and understanding of the Client, Figure 12. The HCS of 20 cm in depth plus topping of 7.5 cm, with all six or four cores filled with concrete at 1.2 m in length were tested. Initially, two levels of end restraints were planned for testing: "no torsion stiffness" of edge beam (HCS as a simple beam) and "indefinite torsion stiffness" of edge beam (fully fixed support of HCS). Unfortunately, the testing of more interesting fixed model was abandoned; the site couldn't wait for those results.

According to *fib* Bulletin 6[1], the shear at interface between HCS and cast in place edge beam was governing design criteria in case of simple beam model, so the inclined bars were added in each opened core, Figures 10-11. Experiments verified the calculations - four reinforced cores were enough for required ultimate capacity of indirectly supported HCS in this case. The mode of failure was predominantly flexural, controlled by the amount of lower reinforcement in the cores, although some splitting between topping and HCS was also observed, Figure 13. Pull-out of new concrete from the cores was not noticed.

Because the experiments were not fully completed and there was no time to wait on their completion, traditional longitudinal beam corbel was returned into construction. At limited length, the indirect support concept was however applied; designers were confident that this solution will be verified. The behavior of this connection has been monitored since the construction time and it was proven satisfactory.

Irregular parts of the floors were designed as cast in place structures, with appropriate connections with precast elements, Figure 14. At main entrance area, four composite columns-towers dominate; each comprises three steel tubes ϕ400 mm filled with concrete. Two of three tubes bypass the first indented floor and support the second floor slab, and all three carry the roof edge. The "piano-shaped" first floor is hanging from the second floor, Figure 14.

The designers were persistent in exploiting precast concept. So, the floor of fast-food and cinema complex was designed as assemblage of HCS and precast beams as well, with some stiffening RC beams where it appeared inevitable. The "Sylomer" anti-vibration pads of the steel frame supports were anchored into topping of increased thickness, Figure 15, or into the RC stiffening – transfer beams.

Foundation and underground garage

At foundation level, building enters deposits of refueled sand, deformable clay-sandy dust and organic clay. Since these layers usually have low and uneven characteristics, it was necessary to replace about 0.6 m of natural soil material with a tampon layer made of compacted crashed stone and gravel.

The foundation structure of 210 m x 120 m in plan comprises 40 cm thick flat plate with inverted drop-panels, without any expansion joints, Figure 16. This concept makes earth and water-proofing membrane works easer, especially if underground water-table is close to the level of the foundation, as expected to be during construction. The space between drop-panels was filled with compacted gravel and sand with thin concrete pavement on the top. Such a layered system allow easy creation of pavement slopes required in unde-rground garage and easy placing and maintenance of rain and technical water pipe-lines. At the same time, it greatly helps slab thermal insulation and serves as additional ballast against lift-up of light building in case of extreme water-tables.

During construction, the underground water table wasn't too high; still it was necessary to slightly lower it by means of temporary partial drainage system and water pumping. If the extreme underground water however occurred, the complete flooding of the underground level was considered. The large concrete slab was poured in blocks of 16.4 m x 16.4 m, of checked pattern to compensate for shrinkage movements.

The huge underground garage volume is prone to substantial seasonal temperature changes, due to the presence of two entrances and large smoke exhausters around the garage perimeter. To avoid thermal problems of mall ground level slab without bottom thermal insulation, the used heated mall air, instead to be exhausted into the surrounding, has been returned from the roof down into the garage space.

Structural analysis and design

With a structural concept and main details defined, the analysis was conducted at five stages:

- analysis of isolated elements such as HCS, precast beams, corbels etc. for local loadings of gravity type;
- analysis of complete, finished structure, including isolated elements as a spatial 3D framed structure for the effects of gravity, wind, temperature, shrinkage and earthquake loads. For those analysis, 3D Etabs model of the structure was created modeling all specifics of this hybrid structure, including particular connections of elements;
- analysis of, by temporary expansion joints separated parts of the bare structure during construction stage;
- analysis of the final temperature and shrinkage effects taking into account effects induced in parts of the structure before closing of temporary expansion joints (initial stage), superimposed to effects to be further developed in the complete structure from joint closing time onward;

- analysis of in-plane diaphragm strength and stiffness of precast floor.

All superimposed (1.0 kN/m^2 - 5.0 kN/m^2) and live loads (3.0 kN/m^2 - 7.5 kN/m^2) were defined by Architect, according to world-wide practice for this type of buildings.

Taking into account construction schedule and long-term measurements of local temperatures, structure was analyzed for temperature change of ±25 ^{0}C in the construction stage. Although it was suggested to designers that, after closing of building envelope no further temperature changes were possible (building is acclimatized during service), the whole structure was checked for accidental temperature change of ±10 ^{0}C. As a result, the bending capacity of perimeter columns was slightly increased.

The earthquake effects were analyzed according to Eurocode 8[2], for ground of class B, peak base-rock acceleration of 12% of acceleration of gravity and behavior factor of q=4,0. Multi-modal analysis, combining effects from two directions, was conducted, along with control of columns for bi-axial bending and shear[2].

The main issue was optimization of number and position of seismic – moment resisting frames for control of lateral deflections, especially in plane of facade. In preliminary stage, the main façade was designed with the use of precast RC vertical panels, to allow anchorage of ceramic-façade elements. After series of consultations with façade contractor, façade steel rails were finally anchored directly into the "Ytong" block elements, which greatly helped in overall structure behavior, Figure 17.

According to domestic regulations, the main design comprises all the necessary for construction details – shop drawings, quite a job in the case of hybrid structures of this kind.

Multi-story garage structure

Structure description

The structure of the open multi-story garage is separated from the mall structure by vertical expansion joint 20 cm wide along the entire structure height, except at the foundation level. As mentioned before, a common foundation slab is designed for both separated structures, with reinforced concrete retaining wall in the façade plane at the underground level.

The overall dimensions of the garage structure layout are 96.0 m × 32.0 m. The garage has five above-ground parking levels with storey height of 2.9 m, and four one-way ramps for inter-level traffic. To minimize restraint forces induced by temperature changes, the structure is divided by expansion joint in axes 16 into two separated parts along the entire height, except at the foundation level, Figure 18.

The garage structure differs from the mall's structure in a way that all RC frames are cast in place moment resistant frames. Due to the total allowable height for the floor structure of 65 cm, it was not possible to apply RC precast simple beams. Besides, as it was possible to locate the shear walls at proper positions, the structure was designed as a combination of RC frames and RC shear walls.

The main structure consists of: precast prestressed HCS floor structure, with 10 cm reinforced concrete topping; cast in place reinforced concrete transverse frames in shorter, north-south direction at a distance of 8.2 m, and reinforced concrete shear walls cast in place, in both directions. Shear walls were designed to resist wind and seismic lateral loads and in the larger, western part are located near the center of the garage layout, to prevent a significant restraint forces from temperature related volume changes. Ramps and some parts of the floor structure geometrically irregular in plan were designed as reinforced concrete slabs cast in place, Figure 18. Beams of the frames were cast in two phases: in the first phase the lower half of the beams was cast, and in the second phase, after the hollow core slabs were mounted, the upper half of the beams, together with topping, was cast in place.

The floor structure was designed as a hybrid structure. Although the shear interface reinforcement between the precast slabs and in situ topping necessary for composite action was not required, the reinforcement loops projecting into topping were concreted into the longitudinal joints between precast slabs at every 1.5 m –2.0 m.

To provide for rigid floor diaphragm action of a composite floor, reinforced joints between precast slabs and cast in place beams were made. Reinforcement along the perimeter of such formed composite slabs was designed for resisting the internal forces in rigid diaphragm, Figure 19. Besides, the additional steel ties were provided in longitudinal direction for connecting the composite slabs and vertical structural elements, to provide the entire structural integrity and secondary bearing system in the direction in which frames did not exist. At the connection of composite floor structure and shear walls which resist the lateral loads, the reinforcement for shear force transfer was designed.

The foundation slab was designed as a solid flat slab 105 cm thick, with upper surface 65 cm lowered in relation to the mall's foundation slab, for providing room for electrical installations situated in this area of the underground garage.

The structure was analyzed and designed for following loads: gravity loads, lateral loads (seismic and wind loads), car impact on the barriers and temperature changes of -32^0 C and +20^0 C for all the slabs, except for the top level slab which was under direct sunlight and exposed to +40^0 C temperature change. Besides, the structure was designed for XD3 exposure class and 90 minutes fire resistance. As expected, temperature related volume changes were the governing criteria in reinforced concrete frame design.

Durability requirements

Special attention in design was paid to durability requirements. The main factors affecting open parking structure durability are restraint to volume changes, deterioration from freeze-thaw cycles and corrosion damage from chloride exposure[3]. The resistance to volume changes due to shrinkage, creep and temperature variations induces forces which can cause cracking, especially in joints between precast and cast in place structural elements. In Belgrade climate seasonal and even daily temperature variations can be very high, freezing can occur and deicing salts are often used in winter. Deicing salts are carried with snow and ice on the undersides of the vehicles. The salty water that melts from cars falls on the floor, often accumulating on surface depressions. The chloride moisture seeps into the concrete, and if the concrete surface is cracked, chlorides can rapidly penetrate the slab.

That is why according to Eurocode 2[4] open parking structures should be designed for the exposure class XD3, which is the class with the rigorous requirements regarding adequate durability insurance. Even more, special measures can be required to ensure adequate structural durability for class XD3 in open parking structures.

So, the garage structure was designed for exposure class XD3 and following measures were undertaken to provide adequate durability: good quality, air-entrained concrete of class C32/40 for all cast in place structural elements, proper drainage of the parking slabs with 1.5 percent slope to eliminate the ponding water, minimum concrete cover of 4.5 cm for all reinforced concrete elements and 5.5 cm for prestressed hollow core slabs, limited crack width for reinforced concrete elements and decompression limit for prestressed hollow core slabs, protection of all steel elements not protected by concrete by anticorrosive agents, high-quality sealants at construction and expansion joints, special quality control of all workmanships, especially of works done in situ. Since the cracks in parking cast in place slabs could not be avoided, even for gravity loads, the traffic-bearing membranes which consisted of a multi-layer elastomeric polyurethane material with an integral, nonskid traffic topping were provided. These water and wear resistant membranes protect the parking slabs against deterioration and leakage and are capable of bridging the small cracks, up to 0.2 mm width, Figure 20.

During the service life, a care should be taken on the structure conditions and its maintenance. It is performed by regular cleaning and inspections of various structural elements and immediate repair upon detection of any damage, as well as by periodical replacement of sealants and membranes, all of which is defined in a separate maintenance project.

Conclusion

The massive use of prestressed hollow-core slabs on the first project of this kind in Serbia was valuable experience for all participants:

- in general, architects and MEP consultants don't like hollow-core floors – they are forced to define and coordinate major floor openings much earlier than usually. As expected, some openings were opened later on, on the site;

- HCS producers - contractors usually define strength, deflections and fire resistance of HCS in their catalogs. What designers and sub-contractor need to know is how to hang MEP installations, how to open a new opening in the floor, how to connect partitions and alike;

- structural engineers need some more sophisticated tolls for more precise analysis of HCS with various openings and specific loading patterns. Indirect support connection of

HCS with cast in place and semi precast beams, or with already finished walls (jump-form technology) is one of the still not well understood issues in HCS usage.

Nevertheless, the challenging structure was completed in one year, with due appreciation of Client and Architect.

Acknowledgement

The authors would like to thank to all participants in this project on the succesful cooperation. Concept and preliminary architectural/MEP designs were produced by Moore Architects from Israel, while the main design was assigned to Slavija Biro d.o.o. from Belgrade. Project management was provided by MACE from UK, while real-estate issues were managed by Colliers from USA. General Contractor was company Porr from Austria, with two main sub-contractors for precast works: Širbegović Company from Bosnia and Hercegovina and Vibrobeton from Croatia. Local contractors were engaged for all of in-place works.

References

1. International Federation for Structural Concrete. *Special design considerations for precast prestressed hollow core floors*. FIB, Lausanne, 2000, Bulletin 6.
2. European Committee for Standardization. *Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings*. CEN, Brussels, 2004.
3. Precast/prestressed Concrete Institute. *Parking structures: Recommended practice for design and construction.* PCI, Chicago, 1997.
4. European Committee for Standardization. *Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings*. CEN, Brussels, 2004.

List of figures

Figure 1
Click here to download high resolution image

Figure 2
Click here to download high resolution image

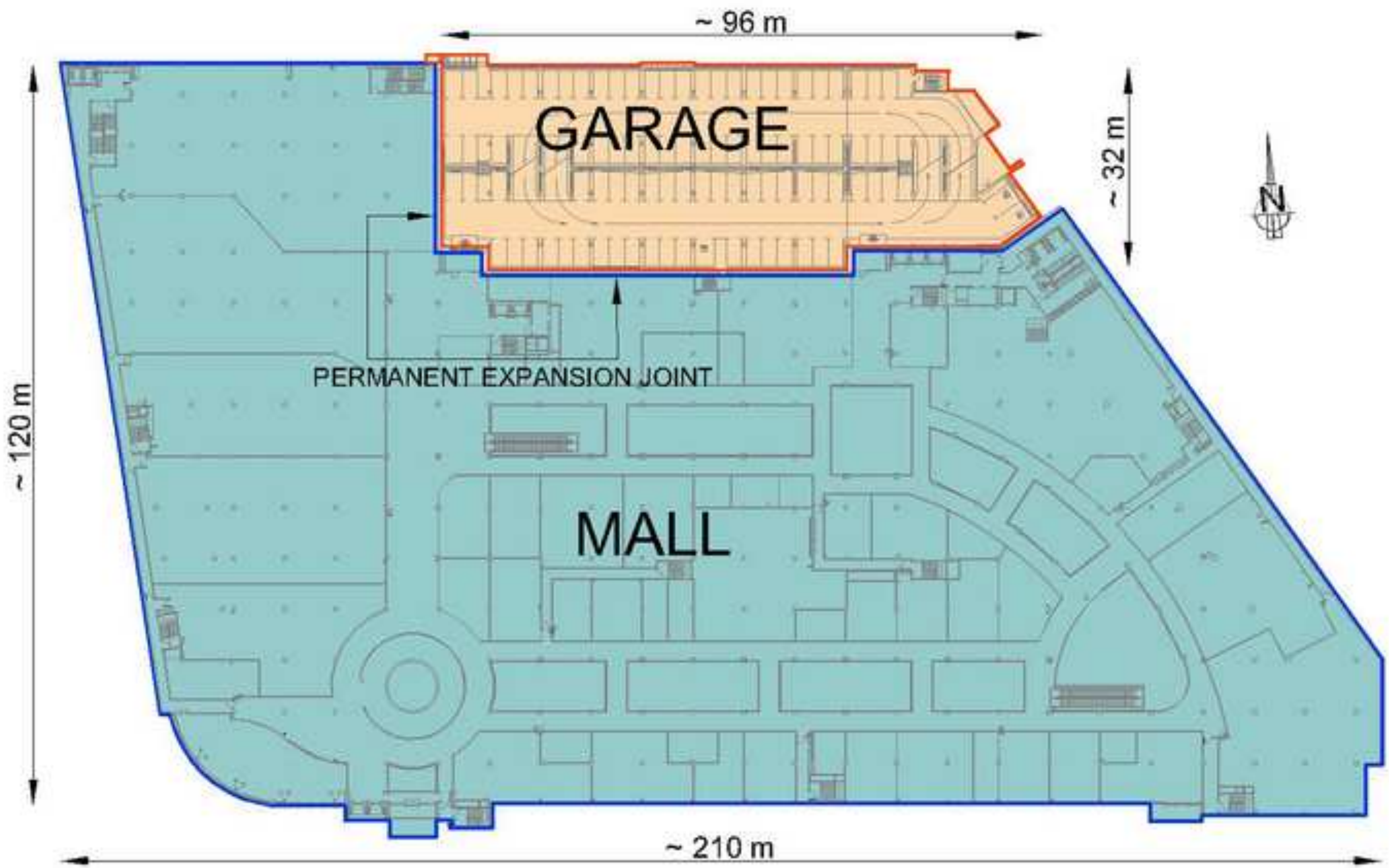

Figure 3

Click here to download high resolution image

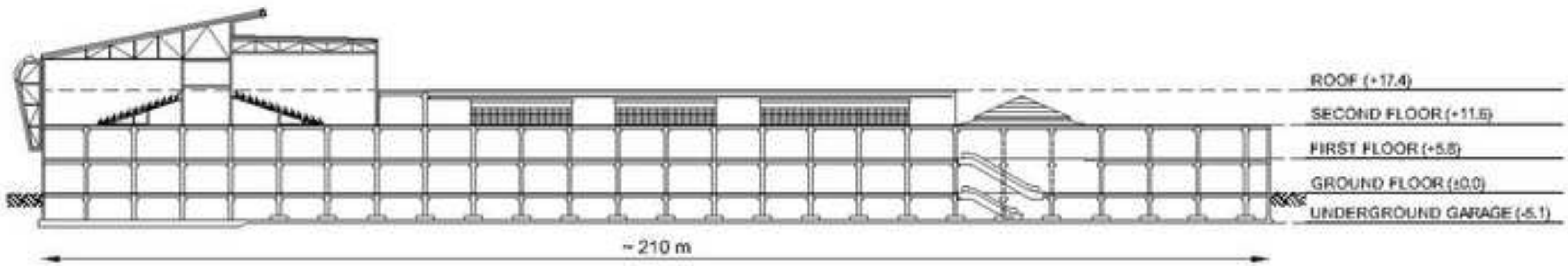

Figure 4
Click here to download high resolution image

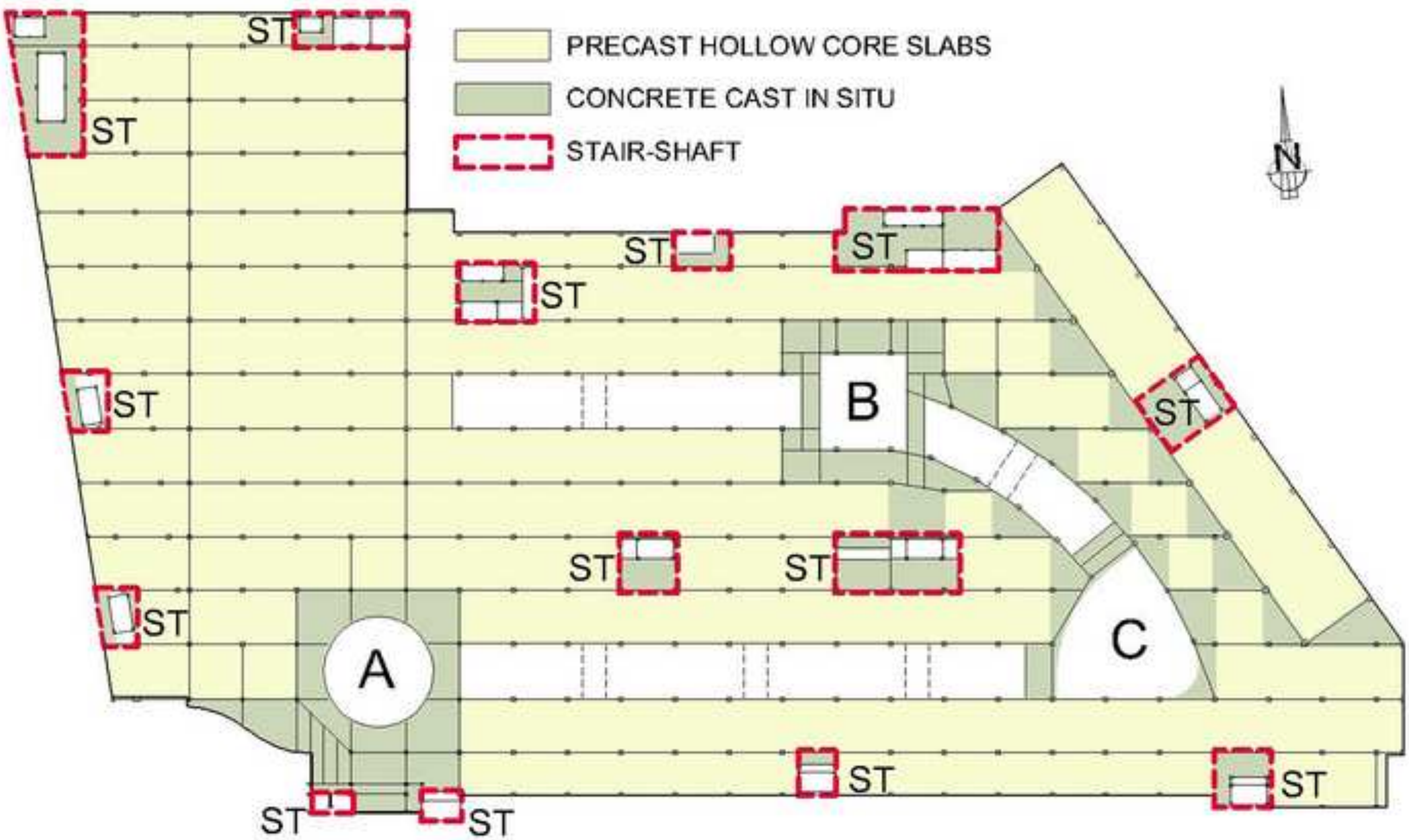

Figure 5

Click here to download high resolution image

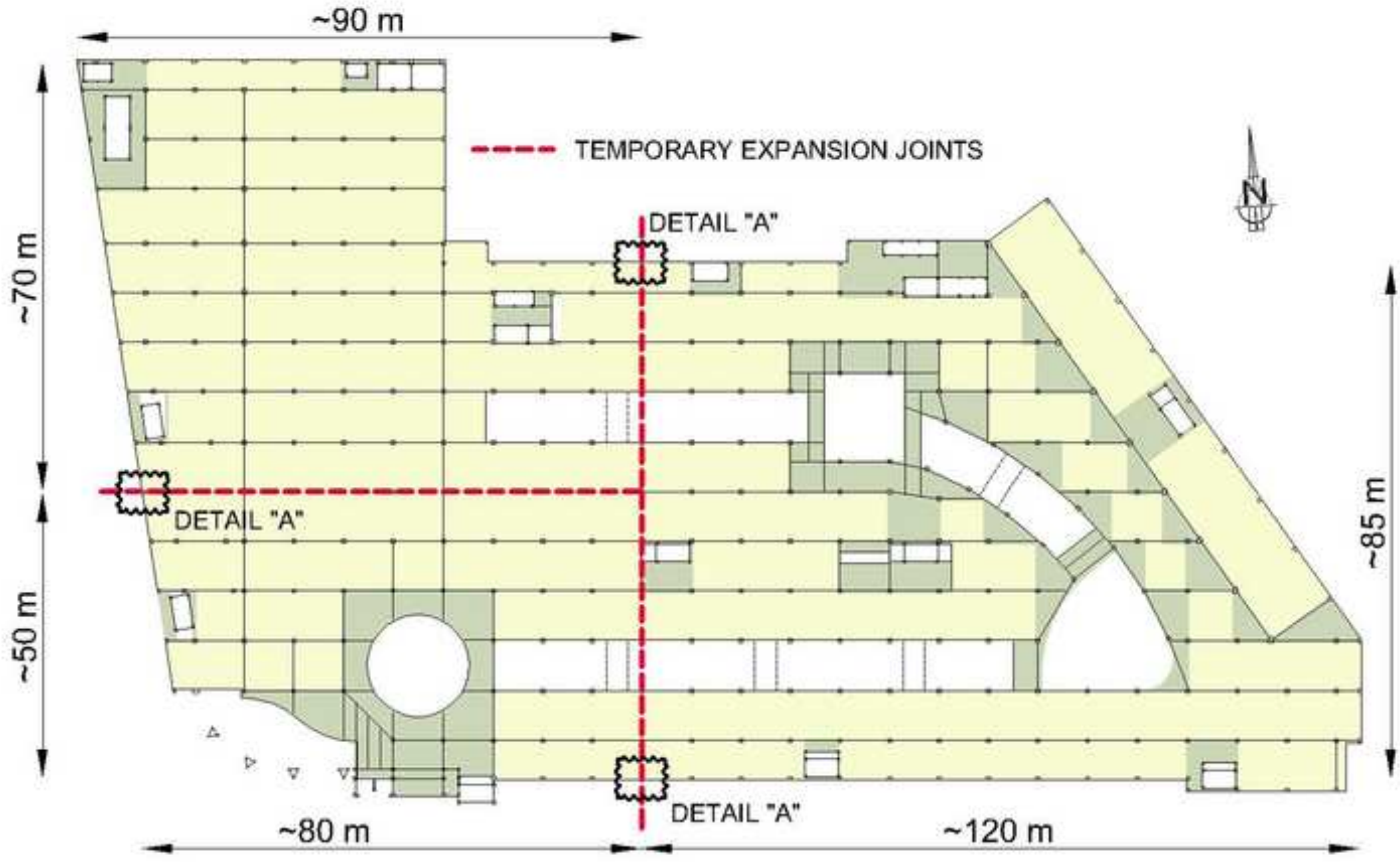

Figure 6
Click here to download high resolution image

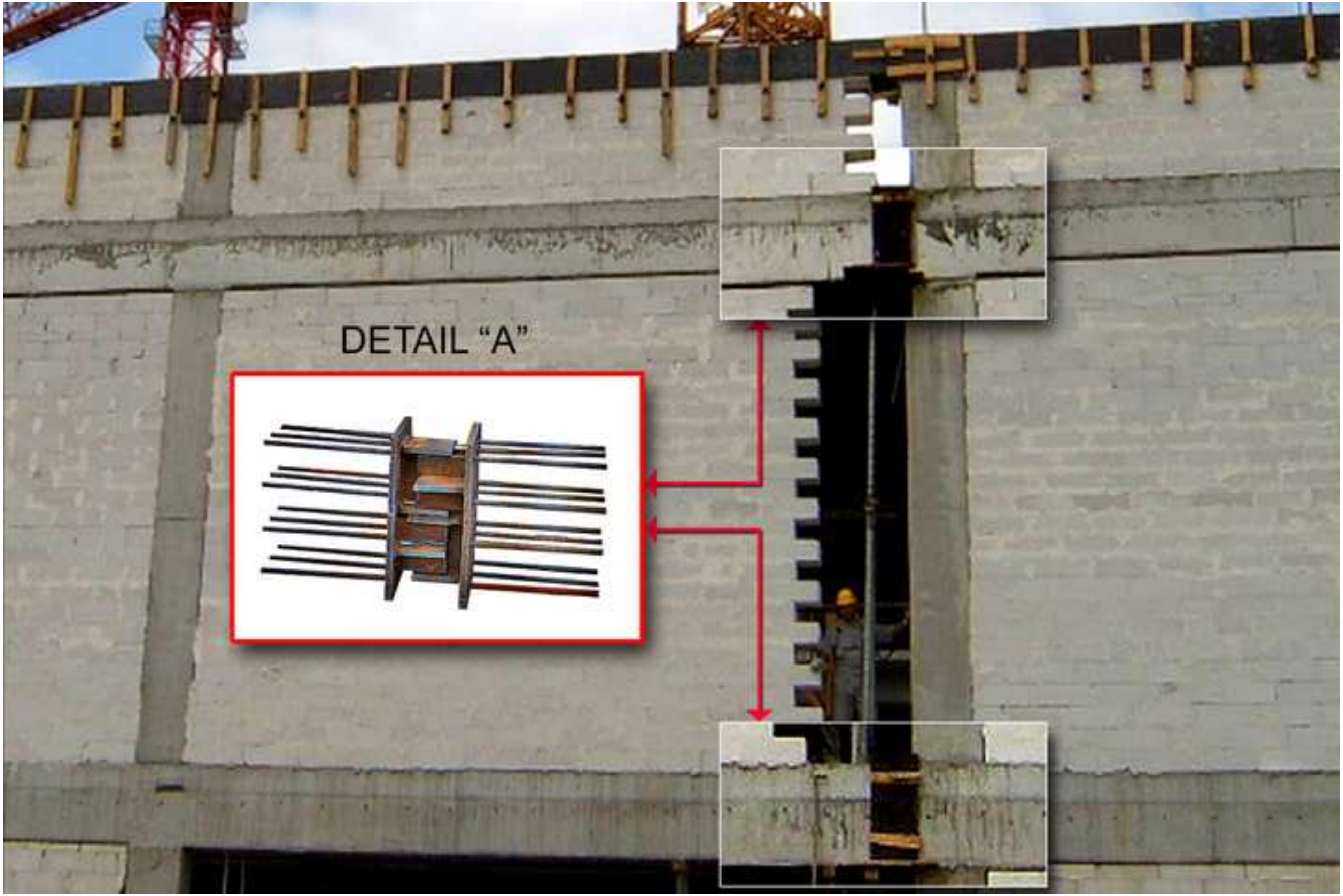

Figure 7
Click here to download high resolution image

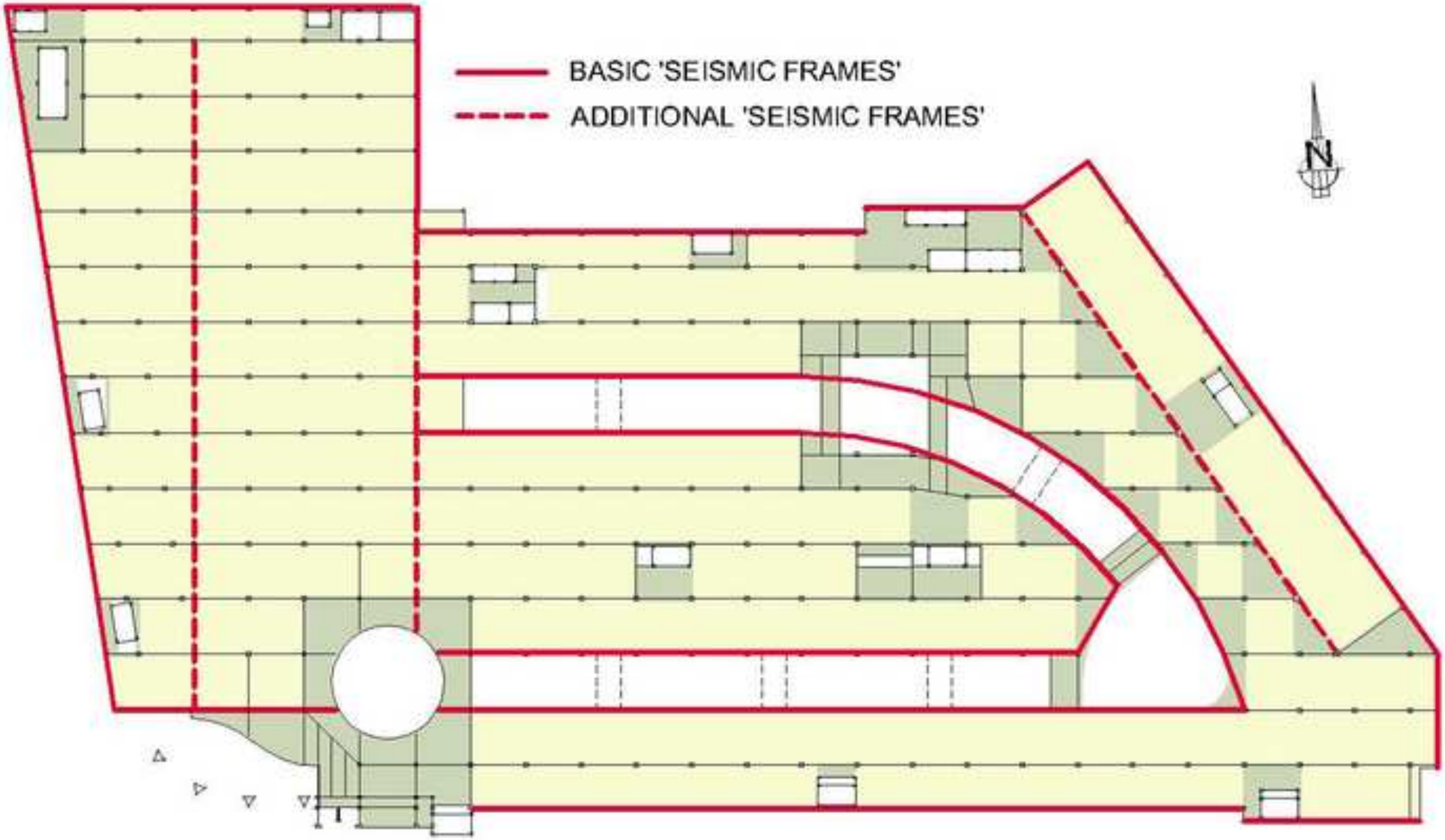

Figure 8
Click here to download high resolution image

Figure 9
Click here to download high resolution image

Figure 10
Click here to download high resolution image

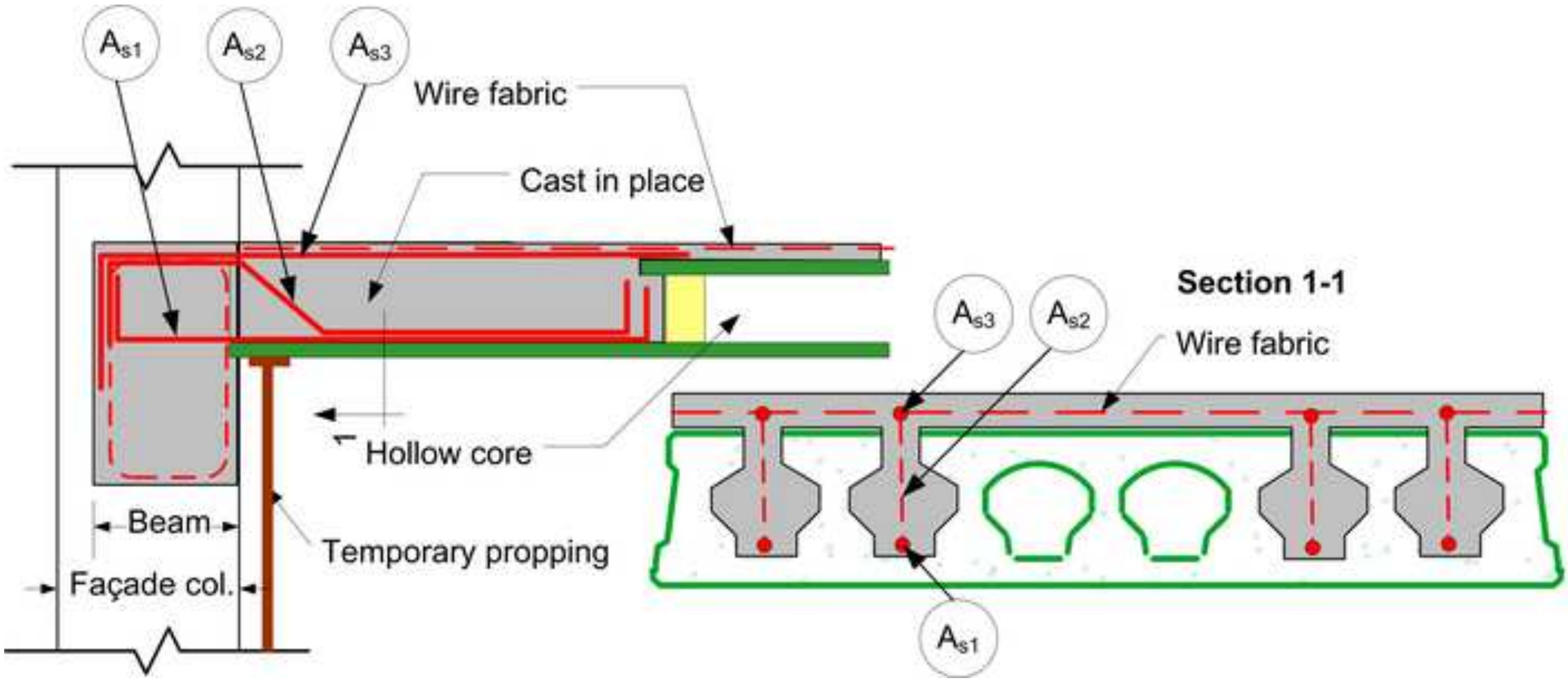

Figure 11
Click here to download high resolution image

Figure 12
Click here to download high resolution image

Figure 13
Click here to download high resolution image

Figure 14
Click here to download high resolution image

Figure 15
Click here to download high resolution image

Figure 16
Click here to download high resolution image

Figure 17
Click here to download high resolution image

Figure 18

Click here to download high resolution image

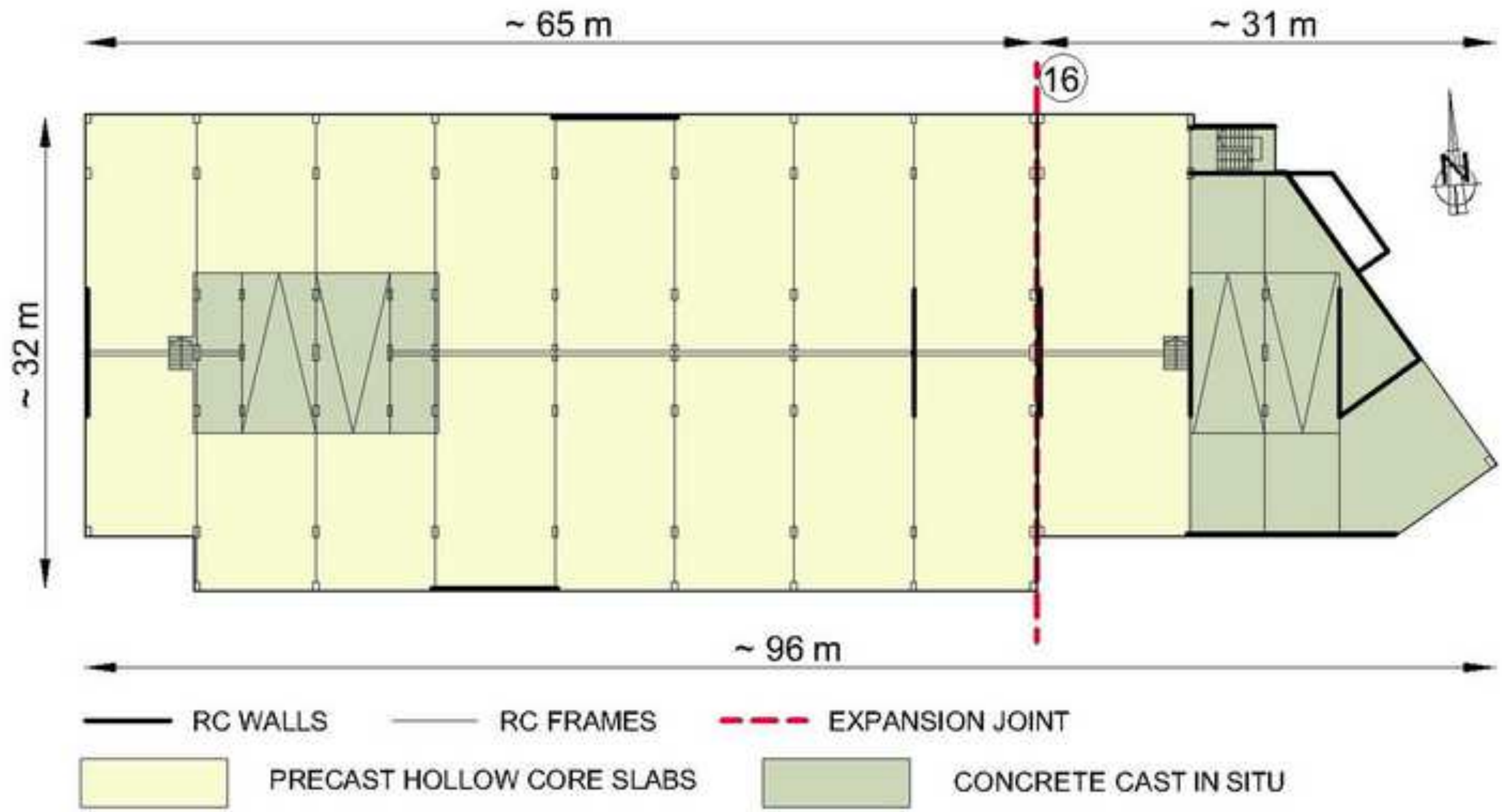

Figure 19

Click here to download high resolution image

Figure 20

Click here to download high resolution image

Author 1 photo

Click here to download high resolution image

Author 2 photo
Click here to download high resolution image

Author 3 photo
Click here to download high resolution image

Author 4 photo
Click here to download high resolution image