# RESEARCH & DEVELOPMENT OF TOTALLY MECHANIZED CONSTRUCTION SYSTEM FOR HIGH-RISE BUILDINGS

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SUMMARY

This paper discusses T-UP method: Totally Mechanized Construction System for High-Rise Buildings based on the consolidation of mechatronics technology and construction techniques. The aim is to mechanically fabricate the individual floors of buildings speedily and continuously. Taisei Corporation has been making great efforts in research toward the mechanization work. Plans to implement this system have already been established and the work is now in progress to actually apply it to a high-rise building scheduled for commencement next year.

## 1. INTRODUCTION

At present the Japanese construction industry and related areas in Japan are suffering from a number of problems. The problem of stagnant productivity and ever-increasing accidents are reflected in the shortage of skilled labor and younger workers, and this is the most serious issue. On the other hand, policies aiming at repletion of infrastructure and a lively flow of private investment in facilities have led to more large-scale projects, and there is a noticeable trend for owners to demand much shorter construction period. With these pressing problems in the background, a large amount of research has been carried into construction robots in many quarters.

However, the labor-saving machinery (including construction robots) thus far used in construction sites is mostly in the form of single-function robots which handle a particular type of work such as painting,(1) assembly of bars,(2) installation of a plate-shaped materials,(3) etc. (Photos 1 and 2)

Although such single-function robots contribute to the mechanization of construction in their own way, the effect is not necessarily of value to the overall project. Looked at in the context of overall building construction work, which consists of a diverse range of trades, functions of such machines are very limited.

To achieve mechanized construction of buildings in the true sense of the word, improvement of mechanization in the areas of design, structural methods, construction methods, materials, will be necessary. Only then will research into robots prove fruitful. Realization of these improvements, however, will lead to comprehensive mechanized construction of buildings, and thus other effects such as high quality, good safety, high productivity, a clean working environment, etc. The authors recognizing that research into comprehensive mechanized construction should start by reconsidering conventional building technologies from the viewpoint of mechanization, organized a project team consisting of engineers from design, construction, mechanical, and materials departments. The aim was to pursue research into a system covering all building technologies, and a comprehensive mechanized construction system for high-rise buildings was announced in October last year. This report describes the research and the machines it is applicable to along with the new structural and construction methods used.

## 2. CONSTITUENT TECHNOLOGIES

The basis of this system is to look at a construction site as a "building production plant." By adding mechatronics technology to the hardware and software of building techniques, which include structural methods, materials, design, and management, a comprehensive mechanized construction system for high-rise buildings was systematically created. It is applicable to multi-storeyed buildings of repetitive plan, such as high-rise office buildings, housing complexes, hotels, and hospitals, and consists of the six constituent technologies described in the following sections.

### 2.1 Initial Construction of Core Tower and Raising the Uppermost Storey

Treating the core structure as an earthquake-resistant element, it is constructed first to take the largest share of the structural burden. The structure on the periphery of the core is made lighter, with the aim of unitizing members and simplifying joints. The uppermost storey is then assembled on the ground around the core, after which, using the core as a support, it is raised gradually using jacks. By treating the core as a support structure in this way, the uppermost storey can be raised with guaranteed stability. This allows work normally done at an elevated location, such as roofing work, etc., to be completed on the ground in the initial stage of the construction schedule. This also makes it possible to install large-scale utility equipment, such as roof-mounted water tanks, and cooling towers, on the ground.

The uppermost storey is anchored to the highest level as the storey of the permanent work. In an example where the floor area of the uppermost storey is about 2,000 $m^2$, the gross weight of the uppermost storey would be about 1500 TONS. Although Fig. 1 shows a center core design, various plans can be adopted such as multi core and twin-core structures, etc. Figure 1 explains the work sequence for the core and uppermost storey.

The construction of the core portion can be of steel or reinforced concrete.

### 2.2 Mechanized Construction under The Uppermost Storey

Below the uppermost storey, an overhead travelling crane and manipulators for various operations are installed to handle the moving in and installation of other members (Fig. 2).

The sheltering effect of the uppermost storey allows work to continue whatever the weather to a certain degree. When carrying out work in snowy areas, an exothermic sheet for melting the snow can be used on the uppermost storey.

### 2.3 Mechanized construction of each floor

Various robots linked to measurement systems using lasers, etc., and other labor-saving machines are introduced for the operations on each floor (Fig. 3). A typical group of machines is listed in Section 3.

### 2.4 Simultaneous Construction of Underground and Above-Ground Structures

In a conventional construction flowchart the upper space is unused during the early stages of construction. If construction at the upper space could be carried out simultaneously with underground construction, the entire construction period would be effectively shortened. To achieve this, the construction method adopted for underground structures is the inverted layered construction method using PCa members.

### 2.5 Mechanized Construction of Underground Structure

An automatic machine, interlocked with various measurement systems, is introduced for the underground excavation work and earth moving work (Fig. 5).

### 2.6 Prefabrication of Components

Materials and structural members pass from the outside plant (primary plant) to the site plant (secondary plant) (Fig. 4), and then to each floor (tertiary plant). Partialization of the materials, meaning prefabrication, standardization, fewer varieties, composite structures, and large units are the aim. As much prefabrication as possible is introduced. In other words, product partialization from the downstream end toward upstream, that is from the tertiary plant to the secondary plant and from the secondary plant to the primary plant, will be carried out. The result is that components are moved in to the site instead of raw materials, thereby improving productivity on each floor as well as ensuring quality control through QC activities in the upstream plant.

The prefabrication process will be described in detail in Section 5.

## 3. APPLICABLE MACHINERY

Of the machinery types applicable to office buildings, which are the model application of this system (Table 1), the ones that are operated in the space under the uppermost storey are shown in Table 2.

As already described, the materials used in the tertiary stage are composite, large-sized components wherever possible. Therefore, the main role of this machinery is to move in the components and position and install them. The use of raw materials such as concrete and fireproof insulation material is limited to supplementary work between components and repair work, such as touching up.

The basic machines are thus limited, as shown in Table 2.

By fitting moduled manipulators, end effectors, etc., on these basic machines, their functional scope can be widened.

Table 1 Summary table of model building

| | |
|---|---|
| Use | Office (3-30F), Shops (2F), Parking (B1, B2), Machine Room (B3) |
| Number of storeys | 3 storeys underground, 30 storeys aboveground, 2 storeys penthouse |
| Construction | Underground SRC; Aboveground S (core portion RC) |
| Height of building | 123 m |
| Building area | 2,310 $m^2$ (698 tsubo) |
| Total floor area | 83,510 $m^2$ (25,262 tsubo) |

Table 2 List of machinery at tertiary plant

| Layout | Module | | | No. of units | Subject material | Role |
|---|---|---|---|---|---|---|
| | Base machine | Manipulator | End effector | | | |
| Bottom surface of uppermost storey | Garter crane A | — | Hook A | 4 | External wall panel | Moving in, installation |
| | Garter crane B | Lazy tongue A | Hook B | 4 | Structural member (column, beam) | Moving in, installation |
| | " B | " A | Hook C | 4 | Floor, ceiling unit | Moving in, installation |
| | " B | " A | " D | 4 | Utility unit (A.C, P.S) | Moving in, installation |
| | " B | " A | " E | 4 | Inner wall panel | Moving in |
| | " B | " A | " F | 4 | Interior finish material | Moving in |
| Interior of core | Garter crane C | Lazy tongue B | Hook G | 1 | Staircase unit | Moving in, installation |
| | " C | " C | " H | 1 | Hot water unit | Moving in, installation |
| | " C | " C | " I | 1 | W.C. unit | Moving in, installation |
| Each floor portion | Vehicle A | Multi-joint | Absorption | 8 | Interior finish light-weight concrete board | Hanging |
| | " A | " | Handle | 8 | Interior finish material, general | Installation |
| | " A | " | Scissors | 8 | Steel column | Welding |
| | Vehicle B | — | Nozzle | 4 | Floor concrete | Joint placing |
| | " B | — | Nozzle | 4 | Fireproof insulation | Insulation |
| | Vehicle C | Multi-joint | Absorption | 4 | OA floor | Installation |
| | " C | — | Absorption | 4 | — | Cleaning |
| | Vehicle D | — | — | — | — | Various measurements |
| | " D | — | — | — | — | Various inspections |

## 4. APPLICABLE STRUCTURAL AND CONSTRUCTION METHODS

The structural and construction methods to which the system can be applied are the "high-rise composite structural method" for the aboveground portion and the "inverted layered method." The latter is new.

### 4.1 High-Rise Composite Structural Method

Many office buildings that have relatively large floor area have been built using a center core design. The high-rise composite structural method is a rationalized method of this type often used in the U.S.A. and other countries. Normally, the core is of reinforced concrete and is built with a systematized form, such as a slip form. In many cases, the frame is made of steel and the link between the girder and the core is a simple pin joint.

The advantages of this structural method are that the time-consuming core is built first, the pin joints are easy to construct, the concrete core is cost effective, and construction is rationalized using slip forming. On the other hand, most of the horizontal force due to earthquakes and wind must be taken by the core. A hat girder is often used for the uppermost floor to increase the flexuaral rigidity of the core and in some cases a belt beam is used. Since the core wall is constructed first and ordinarily the hat girder is used, we selected the high-rise composite structural method as the most suitable for our comprehensive mechanized construction system.

### 4.2 Inverted layered method

The inverted layered method is a method of constructing underground portions of a building which combines the conventional inverted construction technology with prefabrication technology. The underground beams are precast and by using the permanent beam and floor slab as shoring material, a reduction in temporary work is achieved. Fig. 6 shows an outline drawing of this construction method. The standard construction sequence consists of: 1) construction of shoring and foundation piles and erection of center column; 2) excavation of each floor, erection of PCa beams plaing of floor concrete; 3) placing of foundation concrete; and 4) placing of underground column concrete.

As construction proceeds downward from ground level, the constructed portion is closed. Excavation, the moving in of various members, and erection of them in this closed space is a field where the effects of mechanized construction are best displayed.

## 5. PREFABRICATION

Of the six technologies used in the T-UP construction method, the concept of prefabrication of components is crucial.

Under this concept, the place of building production is moved to an outside plant from the actual site. The outside plant is known as the primary plant, and its output is limited by road transportation limits, such as weight, size, etc. The question then becomes how to devise a packing shape ideal for nesting during transportation as a way of reducing transportation costs. This restriction also demands that unitizing and hybridizing, etc., are pushed forward by means of close contact between each manufacturer. For example, the use of multi-layer unit of perimeter air- conditioners and the use of structural blocks with fireproof insulation treatment may be considered.

In addition, to enhance the effects of prefabrication, the physical layout of each plant, the sharing of roles, and making materials into components must be considered as well, while developing time series management for transportation between the plants. The productivity of the building site depends on the inventory of materials and manpower at the site. At sites using this construction method, an MRP (material requirement plan) as used in the manufacturing industry will be introduced to establish an ordering plan and planned production to meet it.

The secondary plant is the facility on site. The fabrication steps previously undertaken at the site plant are completed at the primary plant, so the secondary plant focuses on further hybridizing the products from the primary plant.

The secondary plant is normally located on the second floor of the building being constructed, with the line divided in the same way as the section division of work on upper floors and based on FA production.

The generally higher first and second floors are used for moving in products from the primary plant and booking them into temporary storage and for the secondary plant respectively. The restriction on the secondary plant is the capacity of the lifting crane under the uppermost storey and the effects of wind during lifting.

The tertiary plant is the construction area on each floor. Here, the main work consists of joining and supplementing parts that are moved in and installing them in each section of the work as well as installing utilities, interior, finish, and doing a final inspection. The movement of raw materials, such as concrete, bars, etc., to this location, must be minimized, and by group management of the cranes on the uppermost storey, high-speed assembly is possible. It is important to make the transport one way - that is, to avoid lifting excess materials which have to be carried out, such as packing materials, and forms. The basic idea of prefabrication is to transfer the plane of production upstream; that is, from the tertiary plant to the secondary plant and from the secondary plant to the primary plant.

## 6. EVALUATIONS USING A MODEL BUILDING

This construction method was evaluated by the authors using a model building (Table 1).

Although the items of evaluation as an example of classification include the level of working environment with the contents of construction period, quality, safety, cleanliness, etc., manpower saving, effect of reducing workers, cost of construction, it is impossible to describe all of these in the limited space of the report. Therefore, analysis of only the construction period and construction cost will be given.

### 6.1 Construction period

Trial calculations using the model building correspond to a 20-month construction period, which is equivalent to 70% of the construction period using the conventional method (Fig. 7).

The main factors are as given below.

. Simultaneous construction of underground and aboveground sections (high-speed inverted construction method, jumping form method of construction for the core).
. Adoption of large prefabricated components from the primary plant (hybridizing and modularizing in the primary and secondary plants).
. High-speed transport of materials by means of a group of hat girder cranes installed to the uppermost storey (semi-automatic travelling, positioning function, and division into multi-sections).
. Elimination of climb up of weight lifting crane and replacement separation for reinforcement of temporary facilities.
. Introduction of machinery, including robots, into underground and aboveground work.
. Protection from rain and snow afforded by the uppermost storey.
. Other factors (large-scale OA floor directly fitted to PC floor and joining of core to floor slab with plain bearings, etc.)

## 6.2 Construction cost

The primary reason for the increase and decrease in cost as compared with the conventional method is two-fold. One is the reduction in construction period and labor saving and the other is the introduction of a comprehensive range of machinery.

The former is achieved through schedule control based on the inverted construction method, involving simultaneous construction of underground and aboveground structures, introduction of a range of machinery (crane, robots, etc.), and the multiplying effects of prefabricated components and their distribution system, not the addition of labor nor the extension of working hours. Thus the reduction by 30% in labor hours now possible cannot be seen as a direct reduction in wage cost.

The second reason for increasing costs cannot be avoided due to the introduction of various new machinery.

The trial calculations to the present point in time indicate that the two compete with each other, so construction costs cannot be reduced as compared with the conventional construction method.

In the future, as more construction work is done using this method, the depreciation costs of the machinery may be spread over more projects and this should lead to reduced costs.

## 7. CONCLUSIONS

The construction system described in this report aims to combine several hardware and software technologies that contribute to enhanced building production and to demonstrate the comprehensive effects of the system.

Of the six technologies involved, the concept of prefabrication is not a completely new idea, while the high-rise composite structural method based on a rising uppermost storey with the core as the main axis, is a new concept.

Although our final target is fully robotized construction, this system has been set up by combining existing technologies and certain new technologies. It is scheduled for application to a high-rise building which will commence construction at the beginning of next year, and our staff are currently engaged in detailed assessment work.

Upon completing construction of the building, a report will be presented giving details of implementation.

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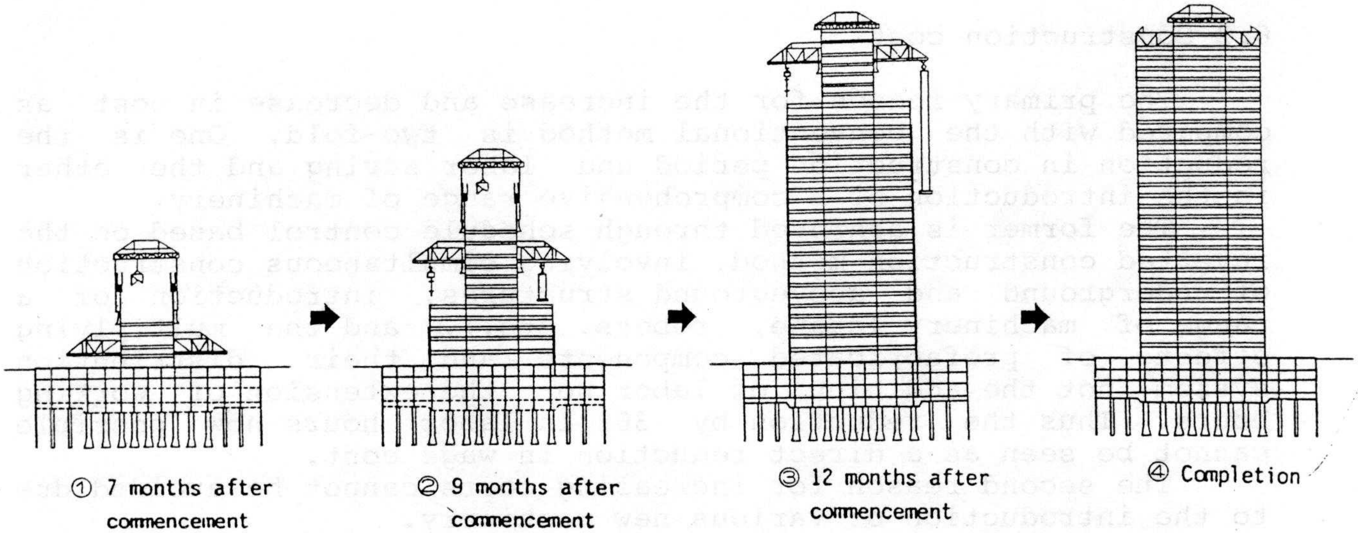



Fig. 1 Core and uppermost storey process

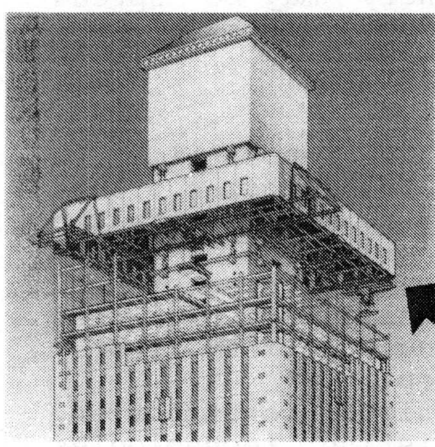


Fig. 2
Initial core work and raising the uppermost storey

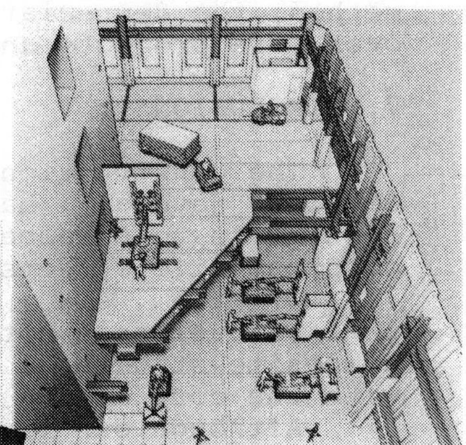
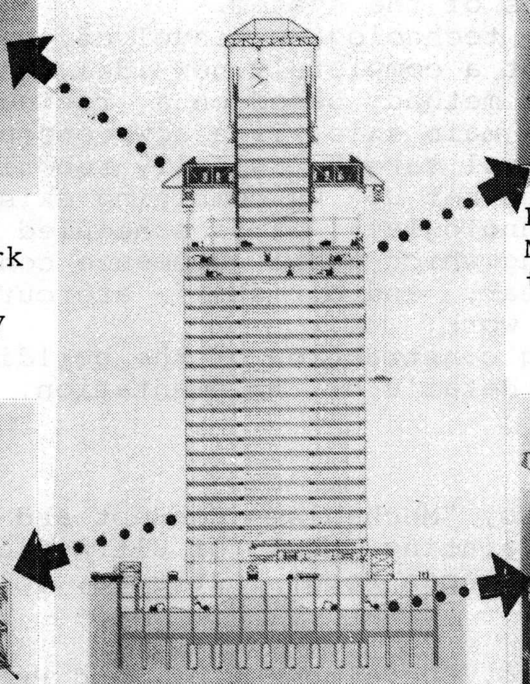


Fig. 3
Mechanized construction of each floor



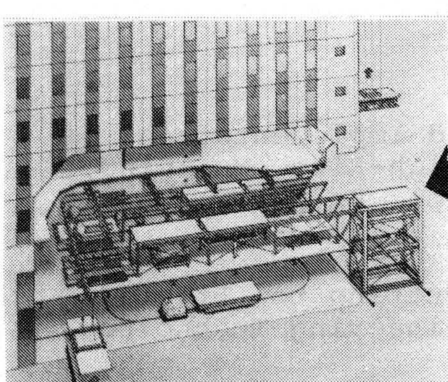


Fig. 4
2F parts plant

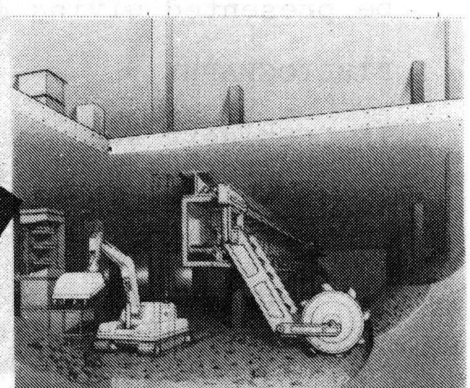


Fig. 5
Mechanized underground construction

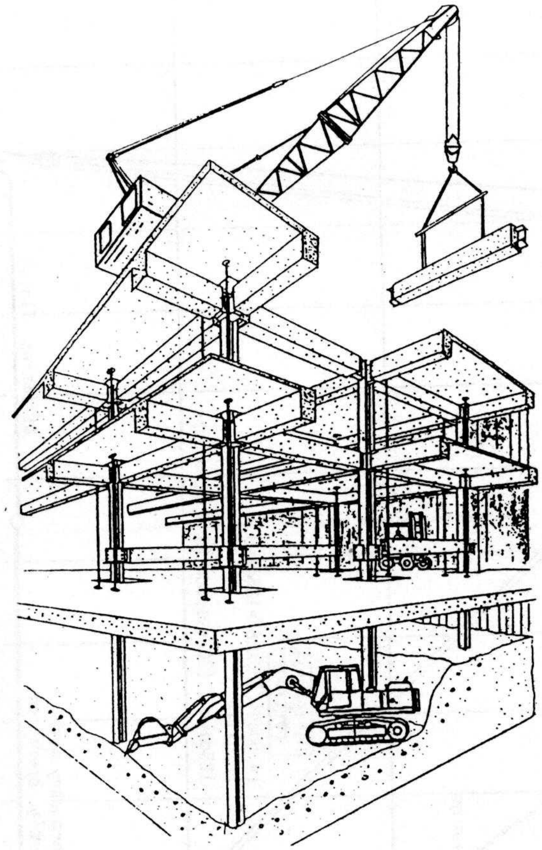


Fig. 6 Outline drawing of construction method


Photo 1
Robot for painting exterior walls

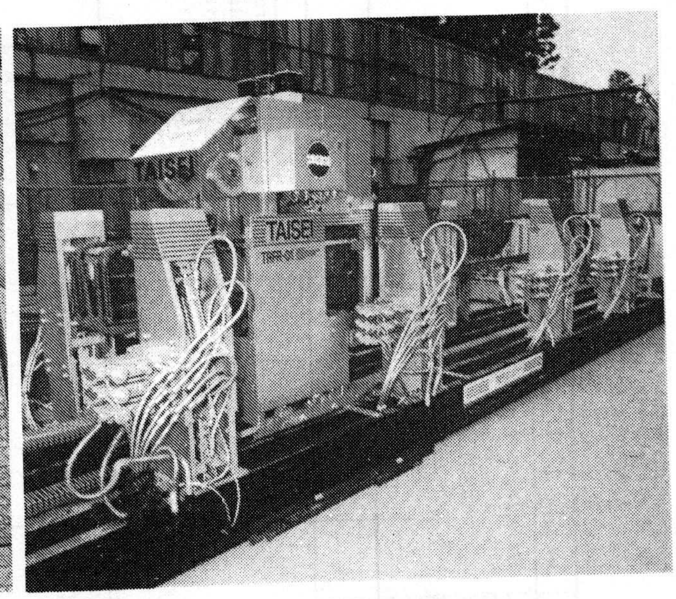



Photo 2
Reinforcing bar fabrication robot

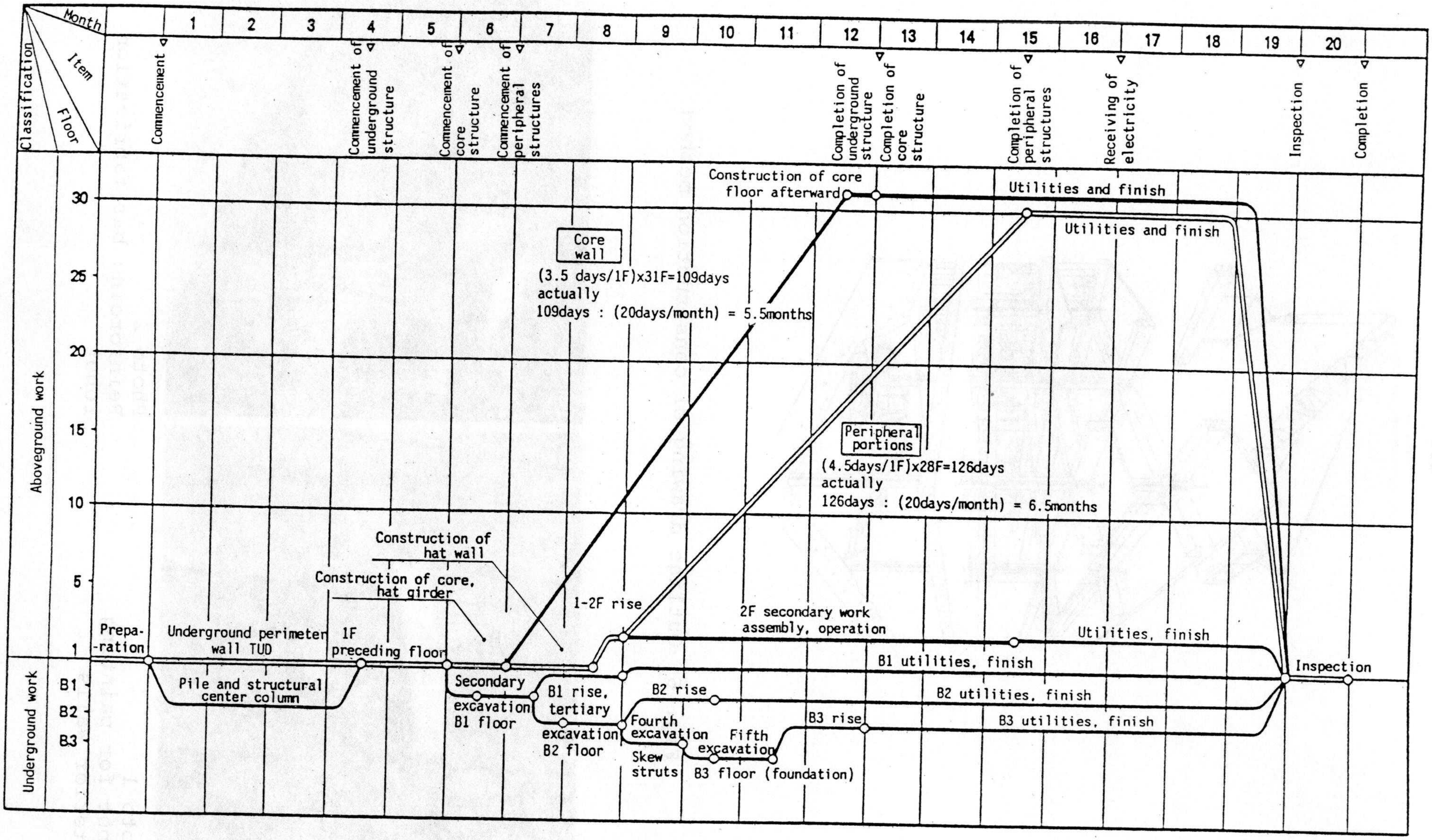



Fig. 7 Construction schedule of model building