Reducing Time in the Construction of High Rise Buildings

By

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Submitted to the Department of Civil and Environmental Engineering in Partial fulfillment of the Degree of

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ABSTRACT

The triangle of project objectives -cost, quality and time- is well known. The relative priorities among them are established by the client/owner. Over the last three decades, special needs pertaining to construction of tall buildings have been established. Particular emphasis has been given to reducing construction schedules. Real estate costs, housing demand, and growth of major cities in developing countries have changed the core concept of traditional construction management and methods.

The purpose of this thesis is to analyze the main factors influencing construction schedules of tall buildings, and to describe measures and methods that have been successfully used in achieving significant time reductions in overall construction schedules.

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I am grateful to God and my family, who have given me everything I am.

Isabel

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1 INTRODUCTION

Time over-runs in construction projects have often been one of the more remarkable 'failure modes' drawing criticisms of construction industry performance. Bordoli and Baldwin (1998) highlighted 50-80% over-runs on 1627 World Bank projects between 1974 and 1988 and an average of 23% time over-run on UK Government construction projects from 1993 to 1994. Kumaraswamy and Chan (1998) found average time over-runs of 9%, 17% and 14% on public building projects, private building projects and civil engineering projects respectively in Hong Kong. The multiple problems arising from such project delays are usually aggravated by their cost implications. Overheads incurred by all participants, as well as the potential claims for progress disruptions by contractors, and/or liquidated damages by clients are the most common consequences.

Among such concerns, many national construction industries or representative organizations have set themselves targets to improve performance levels. For example in the US the Construction & Building Subcommittee of the National Science and Technology Council recently adopted the National Construction Technology Goals (NIST, 1995; CERF, 1997) to improve global competitiveness. Among the goals to be achieved between 1994 and 2004 is a 50% reduction in project delivery times. In Australia, studies target to potential timesavings of 25-40% (Sidwell, 1997).

The particularly dominant commercial pressures in cities like Hong Kong (where relatively high cost of land, volatile markets and short-term business cycles are common events) have generated a collective mind-set aimed at speedy construction. This is further facilitated by the intense competition between local and multinational construction firms.

In Hong Kong the public housing construction technologies have reached a plateau in development that now incorporates certain typical formwork systems and standardized precast elements. Recent time savings by reducing a 6-day floor concreting cycle to a 4-day cycle were not dependent on new technologies, but on reprogramming and tighter controls. However the potential impact of innovative technologies and construction methods on a step-wise (rather than gradual) reduction of overall construction times cannot be disregarded. However the usual increased cost of new technology has to be balanced with the need to achieve reduced times.

Recognizing 'construction time performance' as critical, many investigations have been focused on factors that reduce the overall duration of the construction process of tall buildings. The most relevant methods found are presented in this research.

2 MANAGEMENT METHODS

2.1 Project Planning and Management

The mayor activities in the construction of tall buildings generally are classified into the following packages (Chan and Kumaraswamy, 1999):

1. **Site set-up.** Activities necessary to establish temporary facilities at the work place and prepare the site for subsequent activities, including site layout.
2. **Piling.** Activities necessary to complete the groundwork up to but excluding the ground floor slab, as well as foundations, under slab drainage, basement, etc.
3. **Pile caps/raft.** Activities necessary to construct either the pile caps in the case of a piled foundation, or the raft foundation, including the ground slab floor.
4. **Superstructure.** Activities necessary to erect the load-bearing frame starting from the ground floor column/wall elements, up to and including the main roof and upper roof, as well as precast façade installation.
5. **Electrical and mechanical (E&M) services.** Activities necessary to install the E&M works including electrical, fire services, elevators, water pump and water supply system, wastewater system, town gas, telephone system, storm water drainage, lighting protection, etc.

6. **Finishes.** Activities necessary to complete the building including any brick work for internal partitions, plasting and tiling, carpentry and joinery, ironmongery, steel and metal works, glazing, painting, window installation, wall finishes, etc.

7. **External works.** Other works adjacent to the building including underground cable ducts and drainage, covered walkways, planters, access roads, paving, play areas, pavilion, etc.

The duration of construction is the time span from the beginning of the foundations to the completion and handover of the building to the client. The total schedule can be determined based upon the duration of the above phases that usually are work packages and separate contracts. Durations for site set-up and external works are not critical in determining the overall construction time. Figure 1 shows a typical master program.

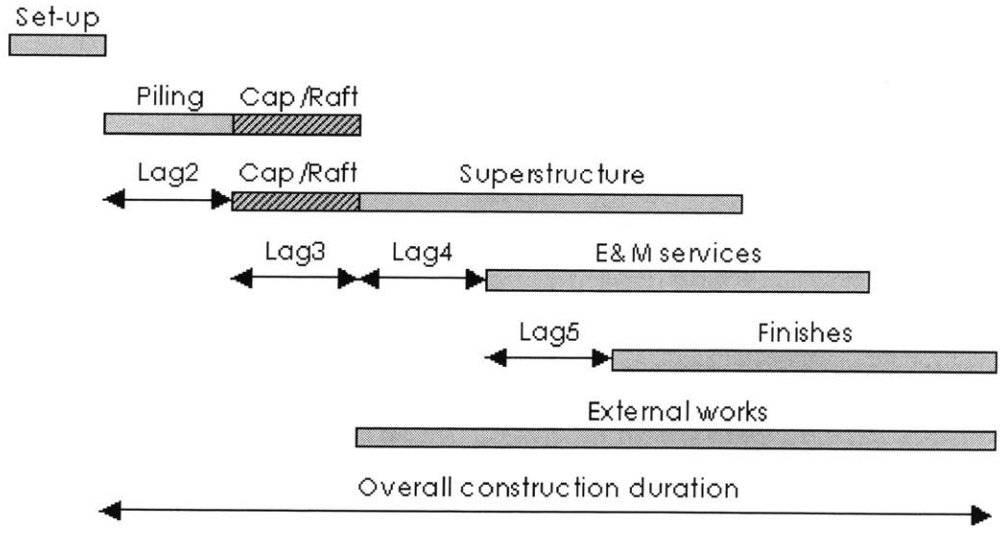

Figure 1 Typical master construction program comprising the five primary work packages (Chan and Kumaraswamy, 1999)

Management strategies for defining these stages as construction packages have been proposed to reduce time in the overall construction duration (Chan and Kumaraswamy, 1999). Since there is common knowledge, or agreement among contractors, managers, and clients as to the general conception and categorization of these primary work stages and the work sequencing of these packages, strategic planning can be performed through a collaboration of all parties. Common durations for certain tasks have been established. Contractors and managers know how long it will take to drill and pour piles of specific dimensions, what equipment to use, and so forth. They also know how to reduce this time through the control of some variables in the present. Furthermore, as in many disciplines, once a better time to perform an activity is achieved ("a new record"), there is both the challenge and the competence to do it better next time.

Based on this knowledge, if the construction durations of every phase can be estimated reliably and objectively in the design stage, time uncertainty will be minimized in the construction stage.

An investigation was conducted in Hong Kong (Chan and Kumaraswamy, 1999) to study construction durations of tall buildings. Data were obtained through a questionnaire survey that identified a set of critical factors influencing the construction schedule of standard "Harmony" type domestic blocks built for the Hong Kong Housing Authority. Qualitative and quantitative project information from a total of 56 standard "Harmony" type domestic blocks completed between 1990 and 1996 was collected from the client and contractors. The researchers found that the seven most important variables affecting the time schedule of this type of structure were: (1) area of external cladding; (2) height of the building; (3) ratio of total gross floor area to the number of stories; (4) type of foundations; (5) information flows between architect/engineer and contractor; (6) presence/absence of precast facades; and (7) type of scheme (rental/purchase). Managers are or should be alerted to the relevance of these factors whenever they have time constraints. The more accurate the information about these areas, the more reliable are the schedules.

While the significance of the variables listed above can be considered, it is also very useful to take into account their influence on others factors (Chan and Kumaraswamy, 1999). For example: (1) the duration for piling works is related to piling cost, type of foundation and depth of foundation excavations; (2) the time required for superstructure construction is affected by the height of the building, labor availability, and the presence/absence of precast facades; (3) durations for E&M services and finishes are dependent upon the 'critical' superstructure duration; and (4) both planned and actual overall construction durations are related to construction cost, presence/absence of precast facades, type of scheme (rental/purchase), and height or number of stories of the building.

From the results of the same investigation, it was found that start-start lags times between consecutive work packages are related to preceding and/or subsequent work packages, along with other (previous) lag times. For instance, (1) lag time 2 in Figure 1 is affected by the piling duration and type of foundations; (2) the durations of cap/raft and superstructure are the critical variables in determining lag time 3; (3) the durations of superstructure and services are the significant variables affecting lag time 4; and (4) lag time 5 is dependent on both the durations of the services and finishes, accompanied by lag time 2 and 4.

Figure 2 shows the significant variables identified as influencing the (a) planned overall duration, (b) actual overall duration, and (c) duration of superstructure construction.

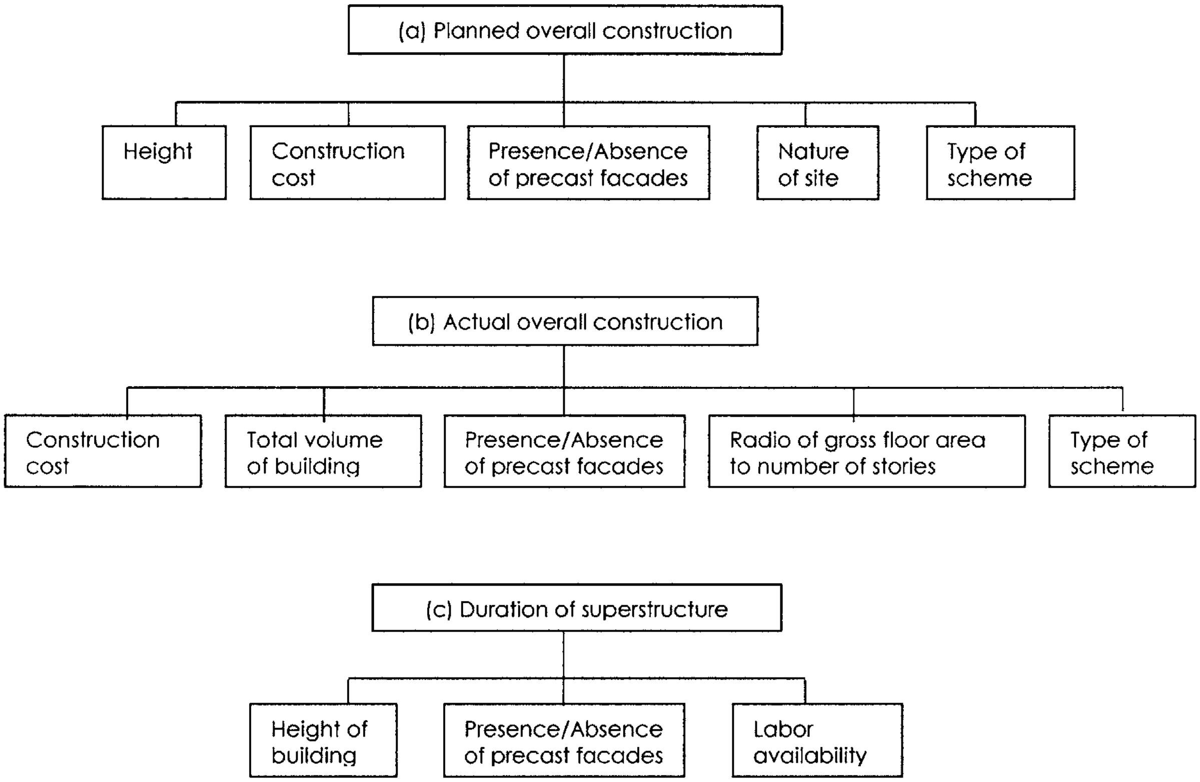

Figure 2 Significant variables identified as influencing the durations of: (a) planned overall construction, (b) actual overall construction, (c) superstructure construction (Chan and Kumaraswamy, 1999)

Effective communication between several groups and hierarchical levels involved in a project emphasizes the need for efficient methods of information processing in the building industry (Ireland, 1983; Walker, 1994; Chan and Kumaraswamy, 1996b). Speed of decision-making involving all project teams;

both formal and informal communications between client and consultant; and, both formal and informal communications between consultant and contractor affect the durations of the primary work packages for building projects. Therefore, to accelerate communications and decision making among all parties, appropriate overall organizational structures, and information communication network systems linking all project teams should be developed throughout the whole life of the project (Chan and Kumaraswamy, 1997b). The roles and responsibilities of those involved in the project team should be defined clearly, and the designated decision-makers also should be clearly identified. Pietroforte (1997) recommended that the scope of project management functions should be broadened from controlling contractual compliance to facilitating the cooperation of project participants and the development of a communication infrastructure.

Other studies conducted by Dissanayaka and Kumarasswamy (in press) indicate that while procurement and non-procurement related factors contribute to cost over-runs, time over-runs are mainly influenced by non-procurement variables such as project characteristics (e.g. complexity level of designs and construction requirements) and client/client representative characteristics.

Many studies of delays in various construction industries have elicited diverse sets of causative factors. Table 1 provides a comparative overview of a cross-section of such factors as identified by the different researchers. It shows that 'materials shortage or late materials delivery' is the most frequently cited cause of delays, followed by 'variations in the project (design changes or extra work)'.

Country where survey was conducted	US	UK	UK	UK	Turkey	Developing countries	Nigeria	Nigeria	Saudi Arabia	Indonesia
Factors causing project delays / Investigator (s)	Baldwin et al. (1971)	NEDO (1983)	NEDO (1988)	Naoum (1991)	Arditi et al. (1985)	Chalabi and Camp (1984)	Okpala and Aniekwu (1988)	Mansfield et al. (1994)	Assaf et al. (1995)	Kaming et al. (1997)
Inclement weather	▲	▲	▲							
Labor shortage / Low labor productivity	▲				▲				▲	▲
Poor subcontractors' performance/ High degree of subcontracting	▲	▲	▲						▲	
Variations in project (design changes / extra work)		▲	▲		▲				▲	▲
Unforeseen ground conditions		▲	▲							
Materials shortage / Late materials delivery		▲	▲		▲		▲	▲		▲
Inadequate construction planning					▲	▲				▲
Financial difficulties					▲		▲	▲	▲	
Delays in design work / Lack of design information			▲		▲					
Poor site management			▲				▲	▲	▲	
Impractical design			▲							
Poor communication			▲							
Inappropriate type of contract used				▲						
Lack of designer's experience				▲						
Inaccurate estimating								▲	▲	▲

Table 1 A cross-section of foundings on the major factors causing delays in construction projects (Kumaraswamy and Chan, 1999)

2.2 Public Sector

Factors such as 'designing with high constructability' and 'minimizing design changes' (for example better briefing and getting it right the first time) are design aspects that were found to be relevant in accelerating construction in the public sector (Kumaraswamy and Chan, 1999). Other factors such as 'adopting more prefabricated components' and 'contractor's efforts in proposing innovative and efficient construction methods' are significant under the construction technology category. The benefits from such factors were magnified by steeper learning curves on site and the generation of inter-team confidence, high team morale and a rapidly attained and sustained smooth working rhythm.

In other research conducted in Hong Kong by Kumaraswamy and Chan, 1999 to determine critical factors facilitating faster construction, it was found that the most important factor as perceived by the Hong Kong Housing Authority (HKHA) and contractors is the 'adequate supply of workforce', followed by other relevant variables as presented below, classified under different categories and ranked by HKHA and contractors:

a) Organization and coordination between all project teams

1st **HKHA.** Adequate communication and coordination between contractors and subcontractors

Contractors. Appointment of a project manager with suitable leadership style

2nd **HKHA.** Adequate communication and coordination within project teams

Contractors. Making fast decisions within each project team and appointment of a project manager with suitable leadership style

b) Progress scheduling and control

1st **HKHA.** Identifying critical activities and setting milestone dates for them

Contractors. Comparing and controlling progress against original schedule on a regular basis

2nd **HKHA.** Sequencing construction activities in appropriate chronological order

Contractors. Foreseeing possible contingencies which may affect the progress

c) Construction technologies

1st **HKHA.** Adequate contractors' experience in building tall projects

Contractors. Adopting a time-saving and standardized floor cycle

2nd **HKHA.** Adopting a time-saving and standardized floor cycle

Contractors. Adequate contractors' experience in building tall projects

d) Design aspect

1st **HKHA.** Minimizing design changes after construction commenced

Contractors. Standardizing the building components

2nd **HKHA.** Providing accurate and complete design drawings to construction teams

Contractors. Design with high constructability

e) Project characteristics

1st **HKHA.** Minimizing variations from client

Contractors. Favorable site conditions

2nd **HKHA.** Clear client brief

Contractors. Adequate pre-construction planning

f) External factors

1st **HKHA.** Government construction strategy

Contractors. Obtaining government permits earlier

g) Material Management

1st **HKHA.** Delivering material to site on time

Contractors. Same opinion

2nd **HKHA.** Reliability of material suppliers

Contractors. Approving material as early as possible

h) Equipment management

1st **HKHA.** Obtaining adequate equipment

Contractors. Same opinion

2nd **HKHA.** Increasing the plant utilization level on site

Contractors. Same opinion

i) Labor management

1st **HKHA.** Adequate supply of workforce

Contractors. Same opinion

2nd **HKHA.** Appropriate labor deployment

Contractors. Same opinion

j) Main contractors control on subcontractors

1st **HKHA.** Close monitoring of subcontractors work by foremen from main contractors

Contractors. Adequate coordination among subcontractors

2nd **HKHA.** Adequate coordination among subcontractors

Contractors. Close monitoring of subcontractors work by foremen from main contractors

k) HKHA control on main contractors

1st **HKHA.** Reserving the right to downgrade or withdraw contractors from pre-qualification list due to serious delays

Contractors. Providing incentives to contractors if projects are completed on time

2nd **HKHA.** On time interim payments to contractors

Contractors. Same opinion

Seven measures were proposed to address the concerns raised by these categories and opinions regarding accelerated schedules (Kumaraswamy and Chan, 1999):

1. Better selection of project managers
2. Adequate training of project architects
3. Include piling with superstructure contracts
4. Adequate training of project managers
5. Prefabricating external works
6. Better selection of foremen
7. Prefabrication of water tanks

They were ranked as listed above.

2.3 Private Sector

As perceived by contractors (Kumaraswamy and Chan, 1999), the five most important factors for faster private sector building construction are (ranked in order of importance):

1. Experience of the client
2. Quick approval of design drawings

3. Contractor involvement in design
4. Suitable client management staff
5. Adequate budget of client

The five most important factors perceived by consultants and ranked in order of importance were:

1. Clear client requirements
2. Consultant/contractor communication
3. Client/consultant communication
4. Fast decision-making by client
5. Selection of suitable contractors

2.4 Comparisons between sectors

As found in the same Hong Kong research described before (Kumaraswamy and Chan, 1999), there exist great variations in building designs and managerial systems between the public and private sector.

Natural divergences in scope, objectives and program priorities in each sector cause these differences, although there are some common factors affecting both sectors such as 'effective information flow'.

On the other hand, while client characteristics such as experience and clear requirements are more important in private building projects, factors such as labor supply and management and contractors experience are more important in the public sector.

If we are specifically concern about time over-runs, non-procurements factors have been found to be more significant in both sectors (Dissanayaka and Kumaraswamy, in press). However, it is important to acknowledge that formulating an appropriate procurement system is a necessary first step towards improving performance levels.

Other authors (Deakin, 1999) have indicated also the potential time saving benefits (among others) obtained through Design and Build procurement for certain types of buildings, regardless of whether they are public or private projects.

It is evident that while certain common strategies may be adopted to reduce construction durations in general, specific measures should be formulated to focus on the specific sector.

3 CONSTRUCTION PROCESSES AND MATERIALS

3.1 Jump Form System to Construct Concrete Core Walls

The use of a climbing formwork systems (sometimes referred to as self-climbing or self-lifting) to construct the core walls of high rise buildings has been successful in different countries in reducing construction times, primarily because the process become repetitive though the whole height of the building.

Basically it consists of a frame constructed from structural steel members over the score wall (http://www.cityu.edu.hk/CIVCAL/home.html). Steel formwork panels are hung from this frame, some supported on rollers. After the concrete walls are poured, the framework is released and rolled back from the concrete face. Jacks then lift or climb the whole frame up one level. All the formwork panels are attached to the frame. This process takes approximately one and a half hours.

The moulds are cleaned after being lifted out of the finished unit and then re-assembled. A thin layer of a steel mould-releasing agent is then applied by spraying it onto the surface of the steel mould in contact with concrete prior to reinforcing bar placement. Inspection of the moulds is then carried out.

Once the climbing formwork is in its approved position, the next concrete wall is poured. The cycle continues, which is normally four days. Faster times have been achieved. However, the limiting factor to faster times is usually the construction of floor slabs, which usually are done as a separate process. See figures 3 through 8, which illustrate the system and the process, formwork.

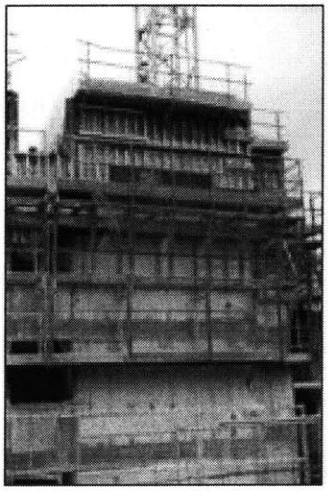

Figure 3 External view of the steel formwork

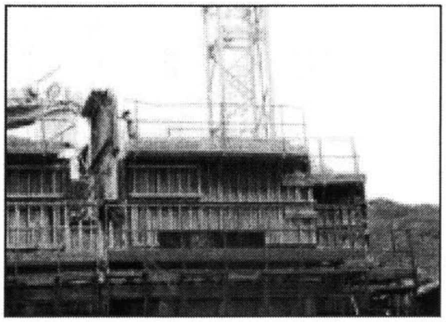

Figure 4 Installation process

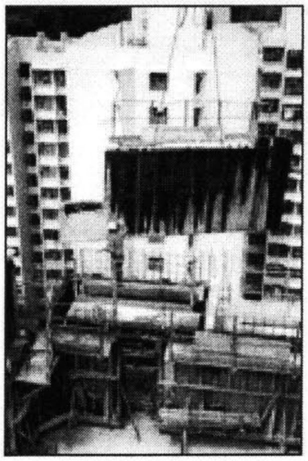

Figure 5 Lift of the steel panel by the tower

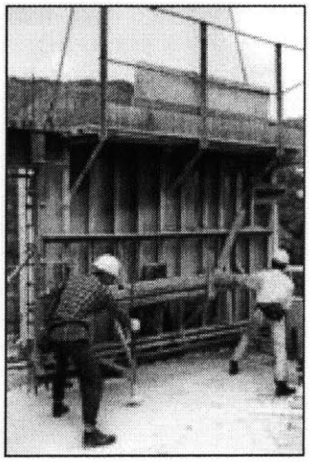

Figure 6 Workers putting the formwork into position

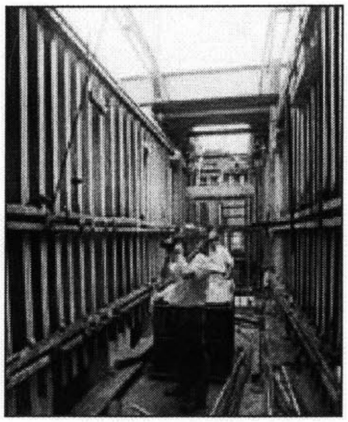

Figure 7 Wall form panels

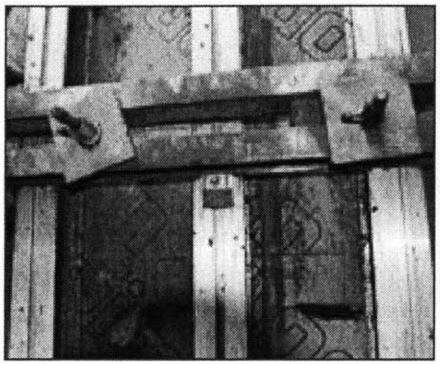

Figure 8 Wall form accessories: tie-nuts, tie rods connection

3.2 Prefabrication of Elements

Prefabrication of elements is another method that has been successfully used to save time in the construction of tall buildings. The repetitiveness of many elements makes this process suitable and very effective. Walls, staircases, external facades, and door sets are common examples of prefabricated elements.

Components are manufactured units, made to predetermined sizes, to be used in buildings. Dimensional coordination governs their design and use, and forms the necessary discipline for industrialized, system, or component building. For example a prefabricated standard staircase component with a rise of 266 cm will govern the floor to floor height of the building in which is to be fixed.

Prefabricated wall cladding panels will closely govern the story height and the length of the building, or part of the building where they are used. The standard frame is usually erected by site work methods, whether mass-produced to standard sizes or specially dimensioned for the particular building project. An accurate tie-in between the respective dimensions of the structure and cladding units is essential (http://www.cityu.edu.hk/CIVCAL/home.html).

Standardized components are joined together to form building elements. Dimensional coordination between all the components is essential, and it is necessary that this coordination be based on a suitable module. When intending to use extensive prefabrication of components, to design the building from the start on a reference grid related to the intended module is required.

The greater the accuracy of the components to be joined, the less the width of the joint, subject to a minimum gap to allow for movement of the components into position and for filling material if required. Basic requirements of the joints are (http://www.cityu.edu.hk/CIVCAL/home.html): (1) allowance for dimensional changes; (2) design should be kept as simple as possible and simple to be fixed; (3) on site concrete connections should be minimized, (4) all joints should transfer loads from one unit to another, or to other parts of the structure; (5) all joints must have the same degree of fire resistance as the structure; (6) all external panel joints should be insulated so that cold bridges that cause heat losses will not be formed; (7) External panel joints should be weather proofed; and (8) they should be easy to maintain.

The advantages of prefabrication are (http://www.cityu.edu.hk/CIVCAL/home.html):

a) Mass production of units
    - Automation of the manufacturing process can save labor and reduce price

- Designers can become familiar with the standard units and have ready access to details

b) Reduction of cost and construction time on site

- Less work to be done on site
- Saving in the use of formwork on site
- Precast units can be erected in bad weather

c) Effective use of formwork

- Steel formwork is normally used and increases the number of uses to 200 times
- Precast units can be shaped so that they are self-stripping thus reducing wear on moulds and labor during construction

d) Improved quality of units

- Factory production provides stricter quality control than on site construction
- Precast units can be closely checked after manufacture

e) Special shapes and surfaces finishes

- Units can be cast in any position, such as upside down, on their sides, etc.
- Colored concrete can be produced by using white cement and a color pigment

f) Casting under cover

- Protection from hot or drying winds

g) Demountable structures

- Bolted connections can be easily dismantled and re-erected in other places

h) Construction over and under water

- No or little formwork is required
- False work is not required
- Minimal disruption to traffic

i) Casting of units before the site becomes available

- Units can be casted and stock piled before the site becomes available, which can shorten the construction time

j) Built-in services and insulation

- Services and insulation can be built into precast units accurately in the factory
- Use of semi-skilled labor

k) Accelerated curing techniques

- Higher turnover per mould and plant
- Controlled curing results in more durable units

l) Solution to the problem of lack of local resources and labor

- Units can be produced thousands of kilometers away from the site

The limitations of prefabrication are:

a) A small number of units required may prove to be uneconomical

b) Special connections, such as special bearings to transmit the vertical and horizontal loads, can add cost to the system

c) Waterproofing at joints

d) Transportation difficulties

e) Need for cranes

3.3 Composite Materials

Two factors in the design of high-rise buildings set them apart from other structures. They are required to resist large lateral loads, and the repetitive nature of the construction requires that the design is refined to enhance the speed of construction and usable areas. Composite construction in high-rise buildings refers to the mixed use of concrete and structural steel in major load supporting elements.

Composite construction is not new, but the widespread use of steel in high-rise buildings outside North America is undergoing a renaissance. (Firkins, 1984; Haryott and Glover, 1984). Determined publicity and research campaigns by steel organizations (AISC, CONSTRADO, KOZAI) have promoted the benefits of composite construction. The reliability of the steel supply and the successful construction of important "pathfinder" high rise projects now result in a composite scheme being studied among other alternatives for all new major high rise projects.

Composite construction endeavors to use the best properties of concrete and structural steel in the most appropriate way:

Concrete: cheapness, local production, unskilled labor, plasticity of shape, good compressive strength, built-in fire protection, corrosion protection, short lead time, reuse of molds, alternative hoisting methods.

Structural steel: prefabrication, off site labor, high strength/weight ratio, high stiffness, high tolerances, smaller member sizes, speed of construction, reduced hoisting, reduced site labor, flexibility of alterations.

The dominant elements where composite construction has been adopted in high-rise buildings are floor systems, columns, and transfer structures. In general terms, composite construction must be compared with other forms of construction to be rated. Early comparisons will be qualitative, such as the matrix shown in table 2, but will become more specific and quantitative as planning progresses.

	Speed	**Flexibility heavy loads**	**Vibration level**	**Struct. depth Ceiling space**	**Simple details**	**Flexibility services**	**Contractors industrial**	**Inherent fire rating**
Steel beam composite slab	excellent	poor	fair	excellent	excellent	poor	good	bad
R C ribbed slab	good	good	excellent	fair	good	fair	good	excellent
R C profiled slab	good	fair	good	excellent	good	good	excellent	excellent
Truncated band beam	good	good	good	excellent	good	good	excellent	excellent
Prestressed band beams	good	fair	good	good	good	fair	good	excellent
14m span	**USER**	**USER**	**DESIGN**	**DESIGN**	**DESIGN**	**CONSTR.**	**CONSTR.**	**CONSTR.**

Table 2 Floor system – qualitative matrix (Nutt, 1988)

Each locality and building industry has its own characteristics; the rate of progress in construction achieved in one city may not be matched in another. Care must be exercised in examining the claims of various materials. Theoretical cycle times are changed on site because of weather, industrial disputes, industry capacity, and construction problems. Nevertheless, early in the planning and design process, a commitment to a particular structural system must be made.

Several construction methods have advantages and can be programmed into the building cycle. A structural steel frame with a steel pan deck floor system can be built very rapidly for large floor areas. Cycle times of 2 days for 2000 m^2 of floor have been achieved in high-rise construction. Grosvenor Place Building, Sydney, utilized a reinforced concrete core with composite steel perimeter columns. The typical floor area is 1900 m^2. The floor system spans 14.4 m and comprises a 125 mm concrete slab on metal pans acting compositely with 530 mm deep steel beams. The 'optimum" cycle time was shown to be 4 days per floor and a 6-day program was planned. The cycle time for a traditional reinforced concrete structure was 12 days. A saving of 8 months in construction time was possible. The hoisting demands help explain this: 134 tons of steelwork, pans, and reinforcement and 275 m^3 of concrete as against 340 tons of formwork and reinforcement and 435 m^3 of concrete for a reinforced concrete system. On-site labor was reduced by 100 workers (Nutt, 1988).

3.4 External Cladding

A building envelope serves the functions of weather and pollution exclusion, thermal and sound insulation (Chew, 1999). It also provides adequate strength, stability, durability, fire resistance, aesthetics appeal, etc. The external walls of traditional buildings are mainly made of masonry and/or reinforced concrete. They are usually finished with cement render and painted. With the advancement of prefabrication, non-load bearing claddings in panel forms have become common especially for tall commercial buildings, where accelerated schedule and architecture of facades have become driving decision factors.

There are many forms of prefabricated cladding panels and each works in conjunction with the structural system of a building. The common forms of cladding are precast concrete cladding, as presented in section 3.2, and curtain walls fabricated of natural stone, metal sheeting and glass.

Curtain walls are non-load bearing external walls of buildings composed of repetitive factory assembled elements. Its dead weight and wind loading are transferred to the structural frame through anchorage points (Chew, 1999). There has been three generations of these systems which have changed according to new technologies and the continue change of needs in the market, such as the continuous pressure to reduce time and budget of tall buildings.

The *first generation (from 1800 to 1960)* was based mainly on the fixing of vertical mullions to which horizontal rails or transoms, frames and insulated panels were attached (figure 9). This system has several limitations such as: a large amount of work on site with the corresponding implications on standards of workmanship and quality control; insufficient allowance for movements due to temperature, moisture, creep and differential settlement (figure 10); water resistance relying solely on gaskets and sealants; and lack of floor to floor flashing which makes it almost impossible to locate a leak caused by water entry at mullion sleeves (figure 11).

The *second generation (from 1960 to 1980)* is characterized by: pressure equalization systems which eliminates reliance on the closure of all holes and relies instead on equalizing pressure in the cavity between external and internal skin (figure 12); panel systems which are completely finished at the factory with consistent quality control (figure 13); and water barriers between floors (figure 14). These second generation systems eliminate the need to complete the structure of the building before beginning the facades. Since this activity is on the critical path of the typical construction schedule for high-rise buildings, the overall construction period can be reduced significantly.

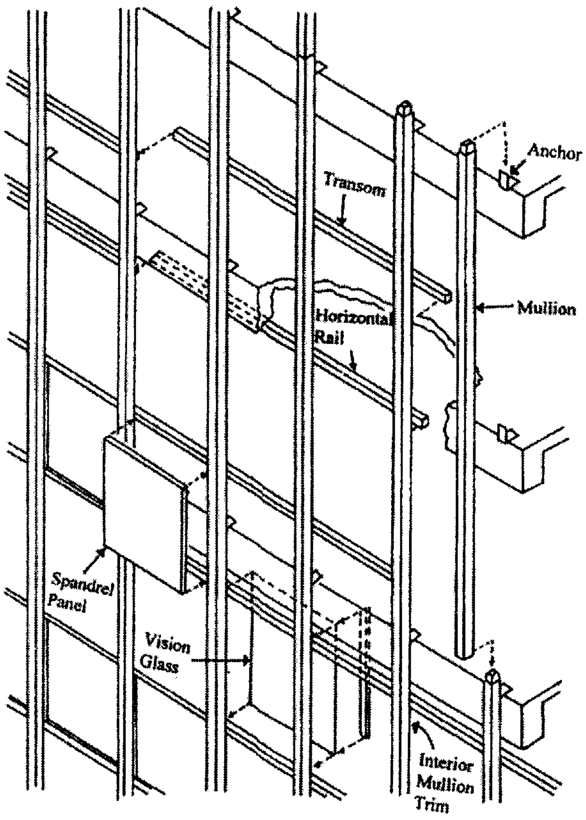

Figure 9 Typical first generation wall

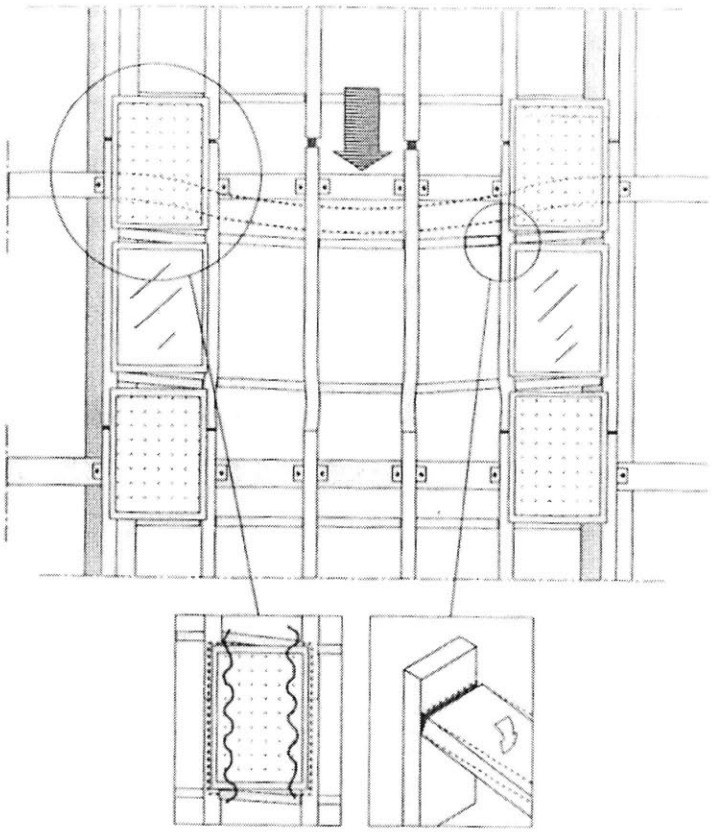

Figure 10 Movements due to moisture, temperature, creep and differential settlement

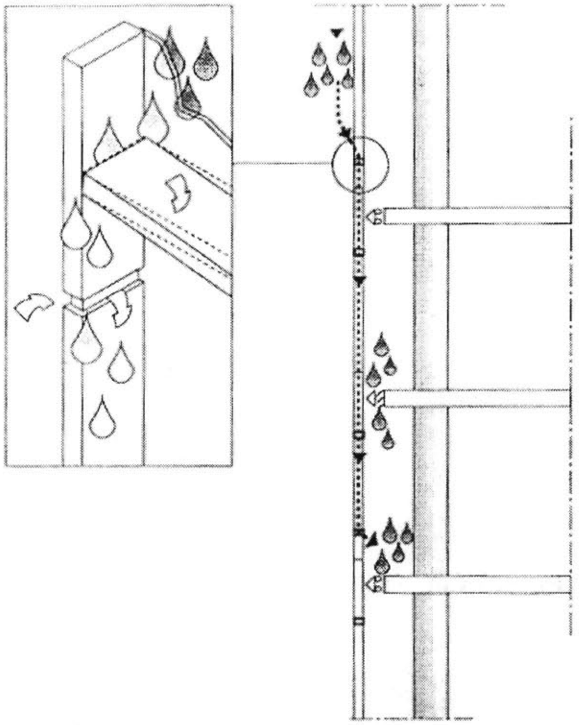

Figure 11 Moisture movements from floor to floor without flashing

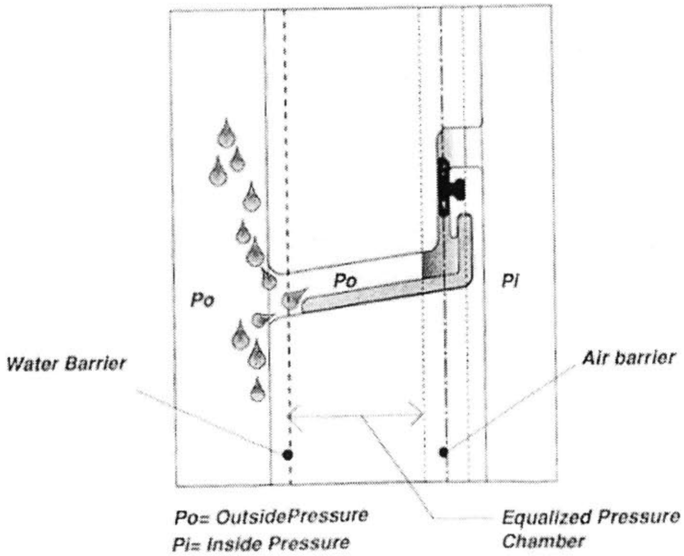

Figure 12 Pressure equalization system

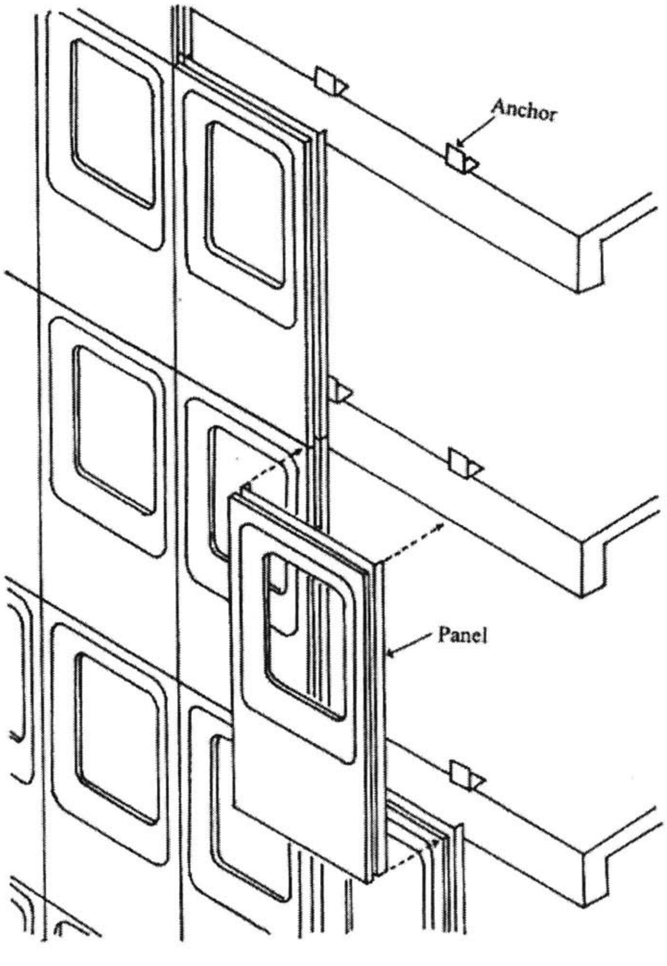

Figure 13 A typical "panel system"

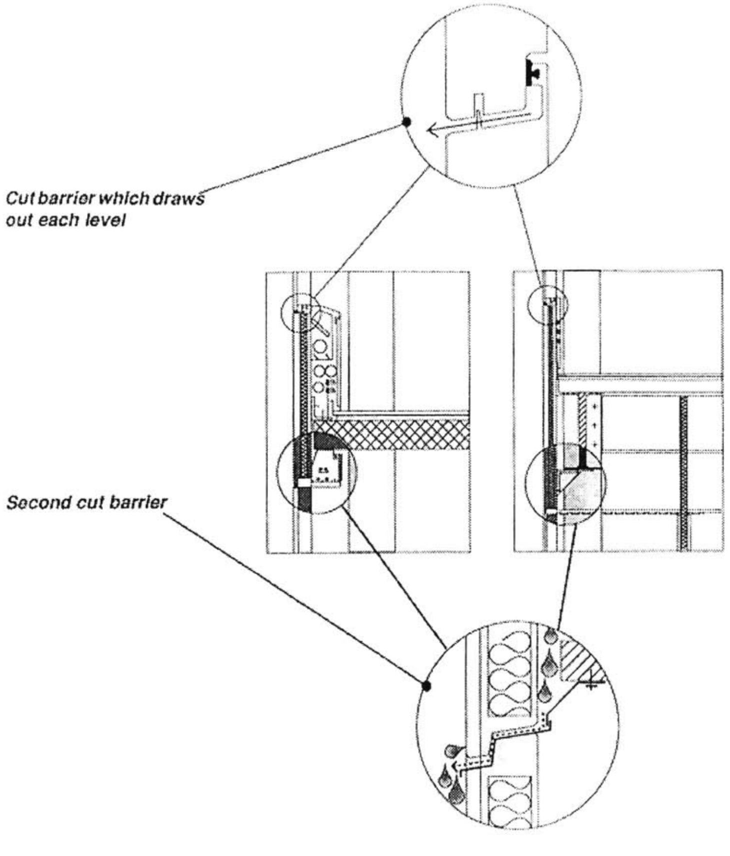

Figure 14 Water barrier between floors

The *third generation (from 1980 to 1990+)* is characterized by improvements of second-generation techniques and the diversification of their use. For example, the wide use of structural sealants and adhesives was observed especially on glazed curtain walls where glass is bonded to the frame.

M. Colomban's envisages that the *fourth generation* (Chew, 1999) of curtain walls will include active walls designed and fitted with devices such as photocells, fluids, fans, exhausts, etc. to accommodate changes in thermal, air quality, lighting, etc.

Improvements in the second and third generation resulted in large timesavings by means of quality control. As mentioned at the beginning of this thesis, facades are among the main factors in accelerating construction or avoiding delays. The first generation of walls was characterized by systematic water infiltrations problems. Trying to locate the non-working area and repair it has been a continuous source of delays in projects and suspension of work activities when the building is operating. It often translated into large expenses, lost of materials, and production time, all of which can cause serious friction among parties directly affected. Devices such as those proposed by M. Colomban's (photocells, fluids, fans, etc.) will provide far more accurate behavior of these systems, therefore allowing increased reliance on them.

4 CONSTRUCTION EQUIPMENT

4.1 Special Equipment

Facilitating horizontal and vertical movement is one of the main tasks in tall buildings construction that must be accomplished in order to develop a schedule that is effective and tight. This means: getting more effective work times; providing materials as soon as they are needed; and reducing time by avoiding repetition of tasks that require closer supervision. Special equipment that has been development to meet these objectives is described below.

Hoists: these are intended for vertical movement only and thus are only able to move in one direction (Chew, 1999). The maximum reachable height is virtually unrestricted in theory, but depends on the particular hoist design. See figure 15.

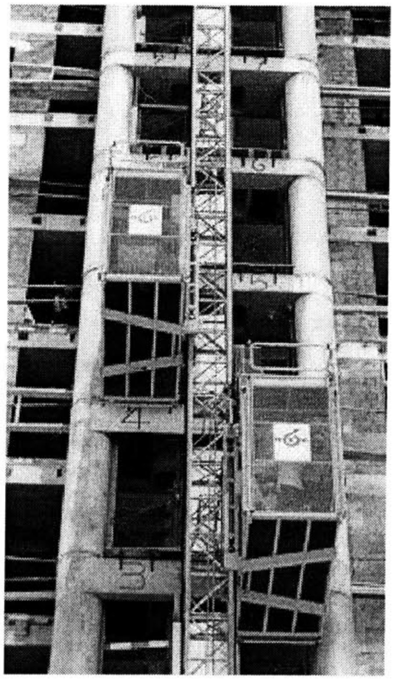

Figure 15 Hoists

Gondola/Swinging Stage: provides vertical movement for workers working in painting, spraying, caulking, sash-sealing, cleaning, etc.; in general for all the external finishes of a building. The gondola is powered by motors, which are either situated at the top of the building or on the gondola itself. See figure 16.

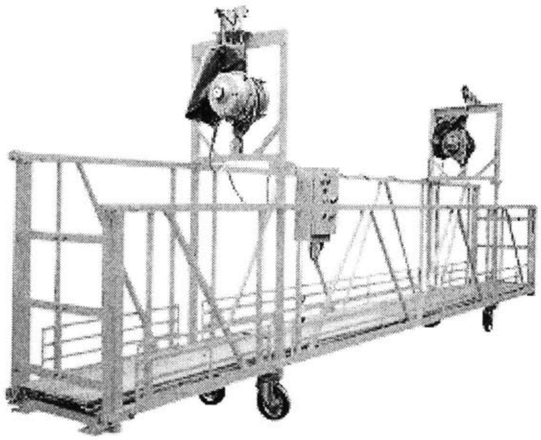

Figure 16 Gondola/Swinging Stage

Work platforms: used for glazing or masonry, they can be matched to any type of building. Platforms lengths are from 1.5m up to 23.4m and payloads up to 3500 kg. Heavy building components and their installation crews can be elevated and positioned exactly with optimum safety and efficiency to heights of 200m and beyond. The machines that operate them are located around the perimeter of buildings. See figure 17.

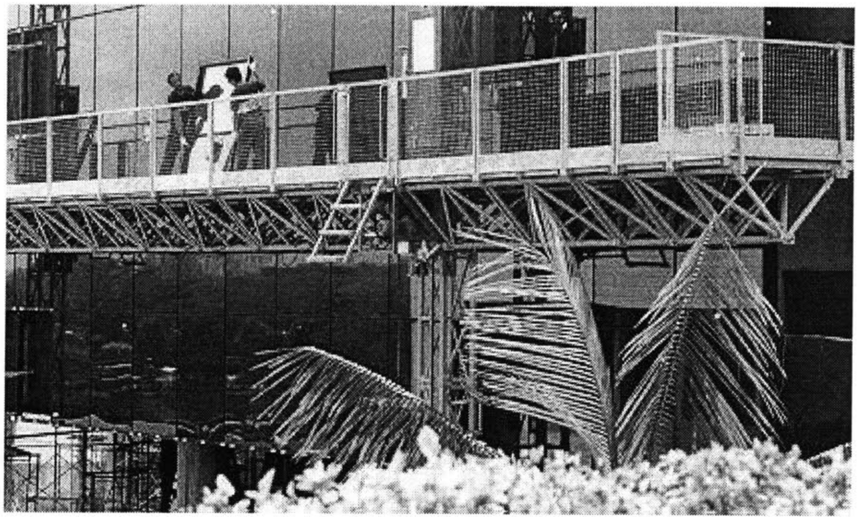

Figure 17 Work platforms

Elevators: moved on tracks are more stable and have higher capacities as compared with a gondola. See figure 18.

Figure 18 Elevator

Cranes: they are generally capable for moving objects in all directions. Various attachments are available for a crane to perform different functions.

Common types of cranes used on building sites are the truck mounted crane, the mobile crane, the tower crane and the climbing crane. Se figures 19 through 22. Which ones should be used depends upon the carrying capacity; maximum coverage; space for assembly, erection and dismantling the equipment; ability to weathervane freely; building height; cost; availability; and speed necessary to complete the project.

Cranes may be fitted with either a derricking jib or a fixed horizontal jib. Counterweights are generally not installed in the mast during the climb up. Tower cranes are tied to the main structure for stability. Shorter tower cranes are often self-erecting while larger ones require the assistance of mobile cranes. Some smaller cranes have no provision for mast lengthening and simply fold down ready towing. For others, mobile cranes erect the mast parts. Some, however, are self-erecting in the sense that they can lengthen their mast by either:

a) Inserting inner tower units through one side below the working platform after jacking the crane on an external sliding tower piece.

b) Inserting tower units through the top of the crane (in this case the platform and parts are attached to a frame that fits around the tower)

c) Jacking the platform and parts on an inner sliding mast section and then attaching two external L-shaped sections to the main tower.

d) Mounting the platform and parts on an inner tower that fits into an outer tower fixed to the ground. Tower units are inserted through the side of the outer tower at ground level.

Cranes may also be climbing in the sense that they can climb up a shaft in the building using only a limited number of mast sections. The crane sits on a slewing ring on an outer frame that is braced on three sides but open on the fourth. The frame extends down over slightly more than two units of the tower. It picks up a tower unit with its jib, luffs in and hooks the unit to a monorail immediately adjacent to the open side. The outer frame is then jacked up hydraulically and the tower unit is slipped in.

Figure 19 Typical mobile crane

Figure 20 Telescopic crane

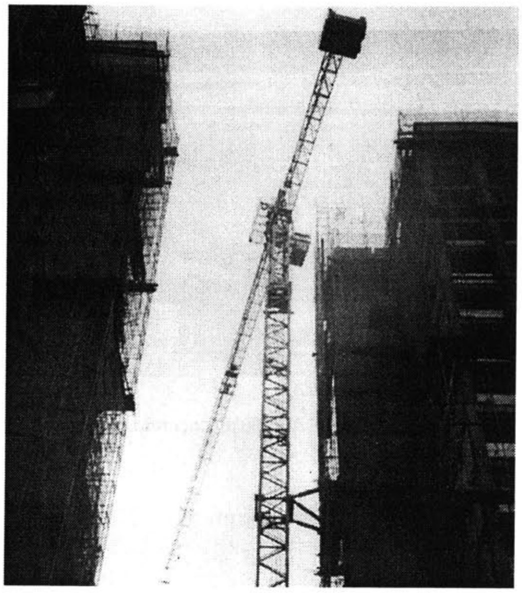

Figure 21 Tower crane attached to the building

Figure 22 Climbing crane located within the building

4.2 Robotics in Construction

The casting, erection, joining, connection and finishing of building components require a high level of skilled manual work on site. The problem with the shortage of skilled personnel in some countries and the need to increase productivity and reduce building schedules has pushed research and development into robotics (Chew, 1999).

Recent progress in robotic technology enables robots to perform sequences of tasks on-site, by interactions with its environment through electronic sensors. An example is Obayashi's "Super Construction Factory" which integrates the concepts of factory automation into the building site for steel structures. Buildings materials and components are delivered to the floor under construction through elevators and are lifted to the exact location of the floor by cranes. Robots then carry out welding and fastening. Upon completion of one floor, the factory is jacked up through an internal climbing system to commence work on the next floor. See figures 23 through 28.

Very similar equipment was developed by the alliance of two Japanese firms, Shimizu Corporation and Mistsubishi Heavy Industries (Kangary and Miyatake, 1997). It was called SMART, and consists of a set of new technologies integrating high rise construction processes, including the erection and welding of steel frames, the placement of precast concrete slabs and exterior ant interior wall panels, and the installation of the various units. The system relies extensively on prefabricated components such as columns, beams, floorings, and walls. Assembly of these components is simplified by the use of specially designated joints, and a real time computer control system is used for the assembly process. This robotized technology consists of five major components: (1) an automated transportation system; (2) innovative steel assembly; (3) a new automated welding system; (4) an advanced lift-up system; and (5) an integrated information-management system. The SMART was first showed in Japan in 1993; 800 people, on average, visited the site every month. It was proved to potential clients that through superiority in technology, higher productivity and improved safety could be achieved.

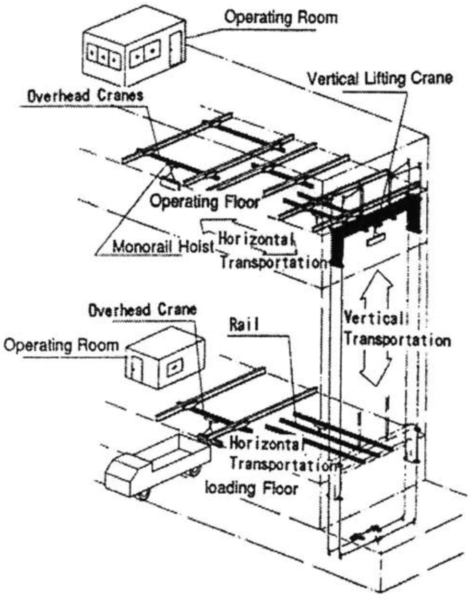

Figure 23 Material handling and assembly systems

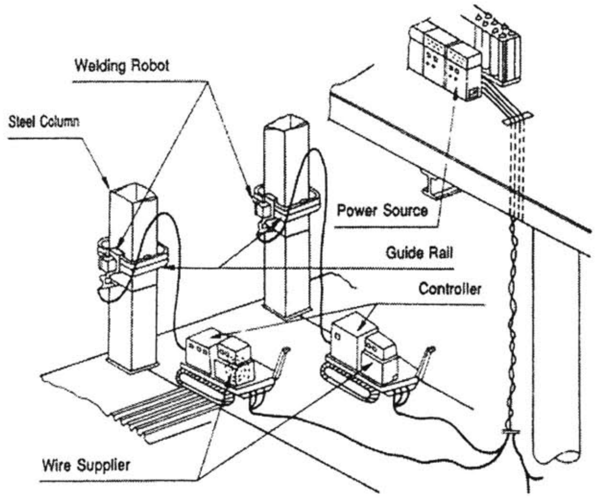

Figure 24 System outline of welding robot

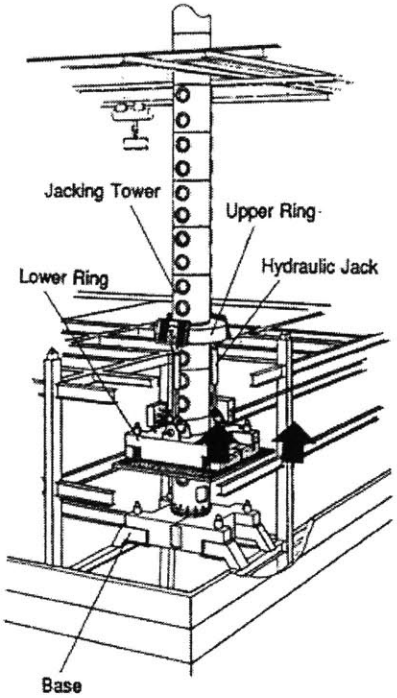

Figure 25 Stage 1 of lifting mechanism: climbing of upper and lower rings

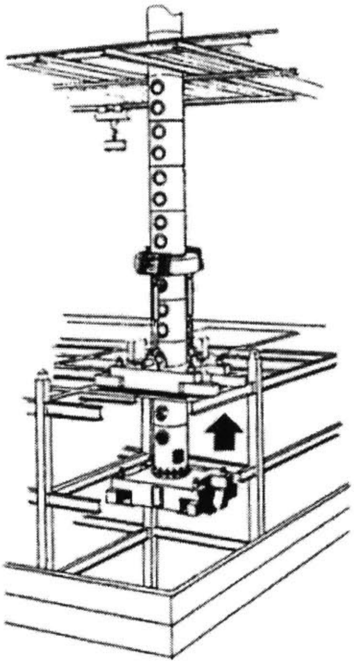

Figure 26 Stage 2 of lifting mechanisms: securing lower ring to beam and lifting upper ring

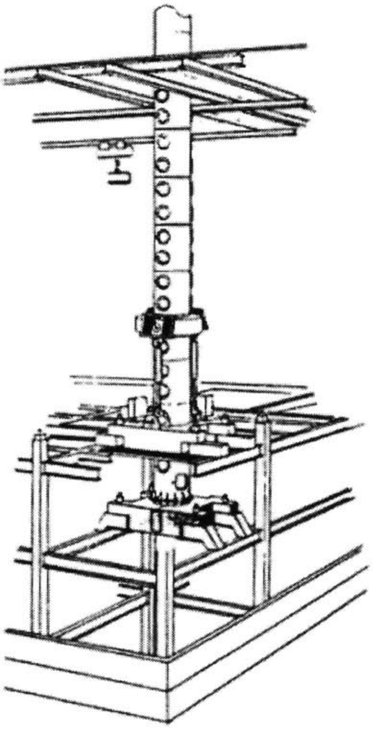

Figure 27 Stage 3 of lifting mechanism: climbing of jacking tower and base

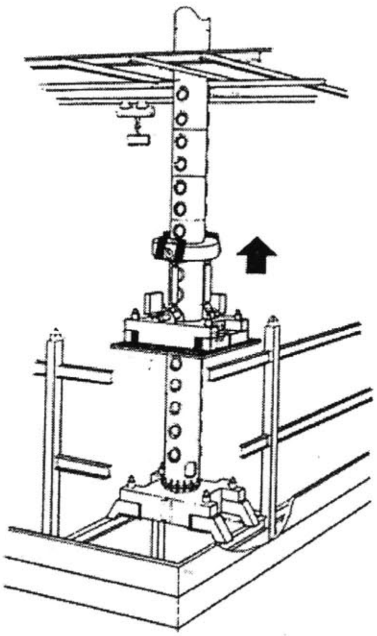

Figure 28 Stage 4 of lifting mechanism: securing base to beam

Another example for reinforced concrete buildings developed by Obayashi Corporation from Japan is called "Big Canopy". It integrates technologies of a climbing canopy, prefabricated components, automated assembly and computerized management systems. The canopy provides protection for the floor under construction from unfavorable weather and environmental conditions. Independent tower crane posts are used as four columns supporting the canopy. The climbing equipment of tower cranes performs the lift of the canopy. Vertical movement of materials to and from the working story is by the use of lifts and horizontal movements by hoists. The movement of the hoists is entirely automated to improve work efficiency. See figure 29. Timesavings accomplished through labor savings on the structural portion of buildings constructed with 'Big Canopy' amount up to 60%. At the present time, Obayashi is building a second and a third 'Big Canopy' building in Japan; and they received an order for a fourth to be built in Singapore (http://www.gcis.com/japan/ar/aj1802e.htm)

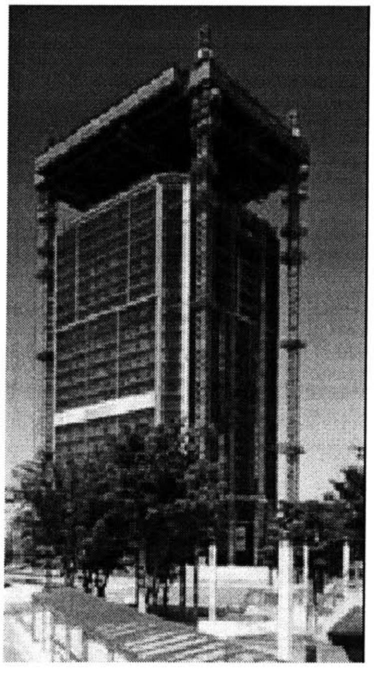

Figure 29 Big-Canopy

Mobile robots have also been used in isolated applications for achieving timesavings and affordable costs. Wall tile inspection, paint/concrete spraying, high pressure water jetting, concrete floor surface finishing, reinforcement lying, and welding, are examples of this trend.

Robotics have been mostly developed by Japanese construction firms, being used and tested in the field but not yet fully accepted and incorporated into standard usage due to high costs implicated. However, this is a trend just starting to develop. Potential for reducing time by allowing 24 hour-a-day results very attractive to the construction industry. My perception is that research on this field will continue until get it to affordable costs, as it has been happening with similar technologic breakthroughs.

5 CONCLUSIONS AND RECOMENDATIONS

The pace of living is changing along with the evolution of the cities of the word; economic factors increasingly are shaping the needs for the new millennium and the construction industry is responding by aiming to speed up building processes. High-rise buildings are particularly important. Government, researchers, and firms of different countries around the world are targeting their efforts towards reducing time in the construction of such structures.

Management methods, construction processes and materials, and construction equipment have been successfully used in reducing time in the overall schedule of tall buildings.

Significant factors that have emerged with regard to applying management methods to reduce construction schedules of tall buildings are: (a) project scope factors (actual cost, presence/absence of precast facades, height and number of stories); and (b) non-scope factors such as speed of decision making involving all project teams, information flow between consultant and contractor and informal communications between architect/engineer and contractor. While certain common strategies can be adopted to reduce construction durations in general, specific measures should be formulated to focus on the specific sector and specific project according to their special and unique characteristics.

Jump form systems to construct concrete core walls, prefabrication of elements, composite materials and external cladding have been extensively used in the past decade to improve productivity, taking advantage of repetitiveness in processes, quality control, optimization in the use of materials, and technological development of new materials.

The implementation of these technologies requires the use of specialized equipment. Innovative equipment solutions facilitate vertical and horizontal transportation in the structures while being erected. Currently, to move materials and personnel vertically, there are several types of equipment that can be used according to the specific characteristics of the buildings: hoists, gondola or swinging stages, work platforms, and elevators. Cranes provide vertical and horizontal movement. There are different types of cranes such as the truck-mounted crane, the mobile crane, the tower crane and the climbing crane. Specific cranes are selected based on the carrying capacity, coverage, cost, and building geometry. Robotics has been applied to construction as well. Big construction companies in Japan implemented artificial intelligence to erect tall buildings through the use of automated elevators, cranes and robots. The diffusion of this concept has been mainly in Asia, where the fourth tall building will be construct using the 'Big Canopy" system.

The intend of this thesis is to identify important research and developments that are being used in accelerating the construction of tall buildings. It is based on the professional experience of the author, with the collaboration of different entities around the world. It is my belief that this trend will be intensified in the near future. It is hoped that this thesis will help initiate and contribute to continual improvement of the schedule performance of the construction industry.

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