THE TALL BUILDING: THE EFFECTS OF SCALE

BY

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Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Architecture
in the Graduate School of
Illinois Institute of Technology

Approved

Adviser

CHICAGO, ILLINOIS
June, 1953
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PREFACE

When a study is made of the effects of changes in magnitude on structures found in nature and those that are made by man it becomes evident that all such structures undergo changes as the scale of magnitude increases and ultimately must be replaced by new structural types.

An examination of various tall buildings indicates that a new structure becomes necessary when certain dimensions are reached.

The project described in this thesis is a new structural type for tall buildings in reinforced concrete. Both structure and function have been analyzed to show their influence on the height of the building and their influence on the architectural expression.

I wish to express my gratitude to Professors Ludwig Mies van der Rohe and Ludwig Hilberseimer under whose influence and guidance this problem was formulated and developed.

I also wish to acknowledge the advice and assistance given me by Professors E. Bluestein, R.F. Malcolmson and Mr. M.L. Mass.
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In the seventeenth century the prevailing opinion on the relation of size to structure was expressed by Sagredo in the *Dialogues Concerning Two New Sciences* written by Galileo in 1638 as follows: "If a large machine be constructed in such a way that its parts bear to one another the same ratios as in a smaller one and if the smaller is sufficiently strong for its purpose, I do not see why the larger is not."  

Galileo refuted this proposition by saying that the size of an organism or artifact has a decisive influence on its structure and its function. He proved his theory with the utmost possible clearness, and with a great wealth of illustration drawn from animate and inanimate structures. He said: "You can plainly see the impossibility of increasing the size of structures to vast dimensions either in art or in nature, likewise the impossibility of building ships, palaces or temples of enormous size in such a way that their oars, yards, beams, iron-bolts and in short all their parts can hold together nor can nature produce trees of extraordinary size because their branches would break

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down under their own weight; so also it would be impossible to build up the bony structures of men, horses or other animals so as to hold together and perform their normal function if these animals were to be increased enormously in height for this increase in height can be accomplished only by employing a material which is harder and stronger than usual, or by enlarging the size of bones thus changing their shape until the form and appearance of the animals suggest a monstrosity.

To illustrate briefly I have sketched a bone whose natural length has been increased three times and whose thickness has been multiplied until for a correspondingly large animal it would perform the same function which the smaller bone performs for its small animal. From these figures . . . you can see how out of proportion the large bone appears, (Fig.1). Clearly then if one wishes to maintain in a great giant the same proportion of limb as that found in an ordinary man, he must either find a harder and stronger material for making the bones or he must admit a diminution of strength."

In this remarkable work Galileo formulates the idea of an ultimate size for structures. He says: "Among heavy prisms or cylinders of similar figure there is one and only one which under the stress of its own weight lies just on

the limit between breaking and not breaking so that every larger one is unable to carry the load of its own weight and breaks while every smaller one is able to withstand some additional force tending to break it.¹

The principles dealing with the effects of magnitude, laid down by Galileo, have since been extended and elaborated in many fields, such as biology, mathematics, philosophy and engineering. Sir D'Arcy Wentworth Thompson in his work *On Growth and Form* cites many examples from these fields. He says: "We learn in elementary mechanics the simple case of two similar beams supported at both ends and carrying no other weight than their own. Within the limits of their elasticity they tend to be deflected, or to sag downwards, in proportion to the squares of their linear dimensions; if a match stick be two inches long and a similar beam six feet (or thirty-six times as long), the latter will sag under its own weight thirteen-hundred times as much as the other. To counteract this tendency, as the size of an animal increases the limbs tend to become thicker and shorter and the whole skeleton bulkier and heavier; bones make up some 8 per cent of the body of mouse or wren, 13 or 14 per cent of goose or dog and 17 or 18 per cent of the body of a man. Elephant and hippopotamus have grown clumsy as well as big, and the elk is of necessity less gracefull than the

¹Galilei, *op. cit.*, p. 126.
gazelle. It is of high interest, on the other hand to observe how little the skeletal proportions differ in a little porpoise and a great whale, even in the limbs and limb bones; for the whole influence of gravity has become negligible, or nearly so, in both of these.¹

Concerning limitations on height Thompson observes that the tall tree tends to bend under its own weight and mentions how Greenhill showed that a British Columbian pine tree two-hundred-twenty-one feet high and twenty-one inches in diameter at the base could not have grown beyond three-hundred feet,² the very limitation on growth for trees anticipated by Galileo.

Analogies to the tapering pine tree are to be found in Smeaton's lighthouse and the Eiffel tower whose profiles follow a logarithmic curve so that the structural strength is uniform throughout their height.

From the examples cited so far, it would seem that every increase in size is accompanied by a decrease in efficiency. This is not always true, and there are many structures whose increasing efficiency due to increasing volume with proportionately decreasing surface continues up to the limits of the strength of the materials. If we consider the case of two similar obelisks of different size it can be shown that

²Ibid., p. 28.
as long as the strength of the material is not exceeded the larger will resist winds that will blow down the smaller, and in the case of similar chimneys the larger may be expected to be capable of standing a greater storm than the smaller. In these cases the overturning forces are proportional to the areas exposed to the wind, while the stabilizing forces are proportional to the volumes, since every increase in size is accompanied by a disproportionately higher increase in volume than in area, these structures become more stable as they increase in size.

The tank for containing fluids is another structure whose increasing size is accompanied by increasing efficiency. It will be discussed in detail later.

A study was made of how these principles are found to be applicable to modern engineering structures. The first study shows a comparison of the spans of different types of bridge structures (Fig. 2). It is seen that each type has an upper and lower limit. The longest plate girder span is six-hundred-five feet, while the simple truss has been used up to spans of seven-hundred-twenty feet and the continuous truss has been carried to a span of eight-hundred feet. Thereafter the span increases rapidly, the arch spanning sixteen-hundred feet, the cantilever bridge eighteen-hundred feet, and finally the suspension bridge reaching a present

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maximum of forty-two-hundred feet with predictable limits in the region of ten-thousand feet. So it is seen that at certain limits the structural system has to be changed.

The reason for the upper limit of structural systems becomes clear by comparing the weights of railroad bridges of different span (Fig. 3)\(^1\). It is seen that a one-hundred-fifty foot span structure weighs four-hundred-thousand pounds whereas a six-hundred foot structure weighs four-million-five-hundred-thousand pounds, thus representing an increase of four times in span in relation to an increase of eleven times in weight. The curve of the graph shows that at six-hundred feet span the increments of weight increase rapidly for every increase in span and it can be expected that the maximum span for this type of construction will be reached not far beyond seven-hundred feet. The steel skeleton of multistory buildings exhibits a similar behaviour. An eight story building requires 0.99 pounds of structural steel per cubic foot of building volume while a seventy-five story building requires 2.22 pounds\(^2\).

In the case of the structural envelope, such as the tank for fluids, the capacity increases as the cube of linear dimensions, but the area increases as the square of


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the linear dimensions. Therefore large tanks will be more efficient than small tanks up to the point where the increasing thickness of plates coupled with limitations on height of the tank offsets this advantage. The increase in weight of structure for oil storage tanks as their capacity increases is shown in Fig. 4A and the decrease in weight per gallon contained as the capacity increases is shown in Fig. 4B.¹

In summing up it can be said that every structure has a maximum and minimum size. For example in the bridge structures there is a region between four-hundred and seven-hundred feet where now one and then another type is used but above two-thousand feet the suspension system reigns supreme, while below four-hundred feet the suspension bridge is reaching a minimum of efficiency. In the final analysis an optimum size may be found somewhere between these extremes and its exact determination will be at its point of maximum efficiency.

¹Data from Chicago Bridge & Iron Company, George Trees, Contracting Engineer. Chicago, Illinois.
CHAPTER II
STRUCTURAL PROBLEMS OF THE TALL BUILDING

The effects of magnitude as stated in the preceding chapter will now be examined in relation to the tall building.

Masonry structures are at their greatest efficiency in low buildings where the thickness of wall required for protection against the elements is sufficiently strong to carry the floors and roof. The maximum height of masonry structure was reached in the sixteen story Monadnock building (Fig.5),¹ built in Chicago in 1891 by Burnham and Root. It has walls six feet thick at the base decreasing gradually through the upper stories to thirty inches in thickness. The internal columns are of cast iron; the external walls are of masonry acting as bearing walls and stabilizing the structure by their mass.

A reinforced concrete skeleton is a monolithic structure in which all the vertical loads are carried by means of columns, while the horizontal loads are resisted by the columns stiffened by the beams and girders. It is characteristic of this structural type, of which the Promontory Apartment Building, built in Chicago in 1948 by Mies Van der Rohe, is a good example, that the thickness of

¹The drawing is the work of a student, Department of Architecture of the Illinois Institute of Technology.
the floor construction may remain constant for every story (Fig. 6A)\(^1\), whereas the columns and girders must increase in the lower stories due to the increase of vertical and horizontal loads (Fig. 6B). The skeleton type permits great flexibility in internal planning, since the vertical members are relatively small and isolated; but the increasing size of the principal members in the lower stories of tall buildings tends to interfere with the use and flexibility of the interior space, and as a consequence, the practical limit on height for this structural type has been about twenty-five stories.

Now it remains to be seen what can be done if it is necessary for a concrete building to go above the practical maximum of twenty-five stories. An office building thirty-four stories high erected in Sao Paolo, Brazil in 1946, was built on a different principle.\(^2\) The horizontal forces were not resisted on each floor level as in conventional skeleton construction but were resisted by wind girders which were placed several stories apart. By this means horizontal wind loads were concentrated at specific levels throughout the height of the structure, thus simplifying the construction by reducing the number of major connections between columns and girders. The section and plan of this

\(^1\) The drawing is the work of a student, Department of Architecture of the Illinois Institute of Technology.

building are shown in Fig.7A and Fig.7B.

A sketch of the front and side elevations of a fifty story concrete building is shown in Fig.8. It has external columns only and every tenth story is a wind girder story which could be used for services and installations. The intermediate floor members do not resist wind action and can therefore be relatively shallow. This building has been limited in depth to about fifty feet, which is about the maximum feasible span of the construction between external columns, the height being limited by considerations of stability to about fifty stories.

So far the examples shown which vary from normal practice are the tall office building in Sao Paolo, and the theoretical study described above.

Assuming that a tall office building in reinforced concrete is required to be of a height greater than fifty stories and a width greater than fifty feet, it may be expected that a new structural system will be necessary due to the increase in magnitude of the building.
Studies were made for a tall office building which embodied a large superstructure of external columns supporting platforms within which a secondary series of skeleton structures would carry the floors. It was decided to develop this idea and the project described is of this type. Structure

The tall office building shown in elevation in Fig. 11 consists of six platforms carried by an external skeleton. The skeleton has columns fourteen feet by sixteen feet in cross sectional area at ground level and these columns diminish in their sectional area throughout the total height of the building. The columns form bays one-hundred-forty feet by one-hundred-eighty feet. The horizontal wind girders at each platform level also diminish in depth as the total height of the building increases. Where columns and girders intersect, haunches have been formed to resist the increased forces at these points. These also diminish as the height increases.

Between each of the six horizontal platforms there are fifteen intermediate stories, seven of which are suspended from the platform above and seven are supported on the platform below. The suspension and supporting members are columns sixteen inches round forming regular bays of twenty-eight feet by forty-seven feet. The middle story in any
series of fifteen stories will be columnless, since its floor is supported and its ceiling is suspended.

The exterior walls to each story height are of glass divided where necessary by mullions.

In constructing the building, the superstructure of six platforms on external columns would be erected first. Then the floors and their supporting columns would be erected for the fifteen intermediate stories within each superstory of the external skeleton.

Among the advantages offered by this type of structure is the reduction in size and number of internal columns below that necessary with conventional skeleton construction. In fact the size and number of columns is no more than is required for a seven story building. Furthermore there are floors which are entirely free of columns every fifteen stories, which could contain halls and auditoriums. The structure has the additional advantage that the number of columns requiring foundations has been reduced to eight, while in the conventional building of similar dimensions ninety-six columns require foundations. The plan of the ground floor (Fig. 9A) is compared with the plan of the ground floor using conventional construction (Fig. 9B). In the conventional construction it can be seen that columns which are eight feet by four feet restrict any possibility of flexible internal planning. However, in the proposed solution, since
major forces are absorbed by the superstructure, the intermediate stories all have similar floor beams, girders and columns, so that if precast and prestressed members are used, similar forms can be employed to cast all these members.

There are, of course, many structural and erectional problems posed by a building of this type which would have to be investigated and worked out in detail.

**Function**

The internal planning of the building comprises in its basic elements a core of elevators, toilets, and stairways around which the offices and their connecting corridors are placed. Plans at different levels are shown in Fig. 10. It will be seen that in the lower stories, the core occupies 48 per cent of the floor area, so that the perimeter of offices is thirty feet in depth. In the upper stories, as the core diminishes in length to occupy 18 per cent of the floor area, larger spaces for offices are obtained at each end of the building. These areas can be used in their entirety or subdivided according to the varying requirements.

As the total height of a building increases, the number of elevators must increase, and in the case of this building type the elevators in fact set the limitation on height. Although the structure could theoretically be extended in height, the elevator core will first absorb all the floor space in the first superstory, thereby preventing
the floor areas on these levels from being utilized for offices.¹

Architecture

The architectural character of the building is a consequence of the decision to use a new structural system and give it expression. The superstructure carrying the major horizontal and vertical forces has been clearly identified from the minor structures which absorb local forces in the intermediate stories. The form of the superstructure expresses the fact that the loads diminish as the height increases. The proportions of the building as a whole are determined as far as the width is concerned by the core in relation to the office space, but the height and the length are proportioned visually. The number and proportions of the superstories both in height and length are likewise, within structural limitations, decided by visual considerations.

¹The elevator system was designed by Messrs. L. R. Smeltzer and H. J. O'Donnell of the Otis Elevator Co. It is based on the use of operatorless signal control elevators with a group supervisory system for dispatching control.
CHAPTER IV
CONCLUSIONS

1. Every structural type, whether an organism or artifact, has a maximum and minimum size.

2. In the tall building there are two limitations on height; one is the structural and the other the functional.

3. When a certain magnitude has been reached in the tall building the structural system must be changed.

4. A new structural system gives the possibility of a new architectural expression.
Figure 15 shows a series of studies for tall buildings in steel, where the external skin becomes the supporting element for the floors. Consequently, the interior space on every floor level is entirely free of columns.

The difference in the material used, in this case, steel, as compared with the study for the reinforced concrete structure which forms the subject of this thesis, is evident by the difference in architectural expression.
Fig. 1. The Effect of Size on Bones.
Fig. 2. Spans of Bridge Structures.
Fig. 3. Weights of Railroad Bridges.
A. Total Weight of Structure.

B. Weight of Structure per Gallon.

Fig. 4. Oil Storage Tanks.
Fig. 5. Monadnock Building. Cross Section.
Fig. 6. Concrete Skeleton.

A. Cross Section Through Floors.
B. Cross Section Through Columns.
A. Cross Section

B. Plan

Fig. 7. Thirty-four Story Concrete Building.
Fig. 8. Fifty Story Concrete Building. Elevations.
A. Proposed Construction

B. Conventional Construction

Fig. 9. Proposed Building. Ground Floor.
Fig. 10. Proposed Building. Plans at Different Levels.
Fig. 11. Proposed Building. Front Elevation.
Fig. 12. Proposed Building. Side Elevation.
Fig. 13. Proposed Building. Cross Section.
Fig. 15. Studies for Tall Steel Buildings.
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