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Integrating Architecture and Structural Form in Tall Steel Building Design

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ABSTRACT

There is an historical relationship between the architecture and structure of tall buildings. The 19th century represents one of the most technically inventive centuries. As a result, it is expected that innovations in tall building architecture would come from those who envisioned the varied use of new materials and means of construction. The development of cast iron as a building material and the invention of elevators paved the way for tall buildings that were unimaginable only a few years earlier.

Structural engineers are principally concerned with the structural form of a building, whereas architects are concerned with the harmonious integration of the building functions, forms, mechanical systems, as well as the building itself. It is through their collaboration that complex buildings can be designed to the highest aesthetic and structural standards. This paper places the integration of structural and architectural design in an historical perspective and discusses the current approaches to the integration of structural and architectural design for high-rise buildings.

INTRODUCTION

The issue of integrating architecture with structural design is a complex one. When structure is expressed, it is expected to look elegant, appealing, and above all, structurally correct. Harmony between structure and architectural form is the key to the success of expression (Ali, 1990). Ideally, the structure should visually clarify and enrich the form.

The notion of architecture as a structural art – the combined art and technique of designing, shaping, and decorating the stone, iron, wood, and

glass of which a building is composed – was overwhelmed in the 19th century by the various classical revivals and a general rejection of the machine and industrialization (Condit, 1964). Giedion (1967) refers to the “cultural schizophrenia” of the 19th century in its desire to hold on to tradition while integrating and utilizing science and technology.

A small arch bridge, built between 1775-1779, over the River Severn at Coalbrookdale, England was the first cast-iron structure. Between 1819 and 1826 Thomas Telford created the first suspension bridge over Menai Strait, leading to the Brooklyn Bridge (1869-1883), a cable suspension bridge designed and constructed by John and Washington Roebling. Gustave Eiffel demonstrated the structural principles of the two-hinged arch and crescent-shaped arched truss in the Garabit Viaduct (1884), which would become the prototypes for his famous tower in Paris (Ali and Armstrong, 1995).

From the structural point of view, the architectural solutions must utilize and exploit the structure to the fullest extent. Since architecture includes a technological component, the buildings should express the structural system as well as its behavior, materials, and construction. Today we are obliged to search for new ways of expressing and understanding the engineering and scientific language of modern architectural design.

Structure and aesthetics are also related through efficiency, lightness, elegance, and the principles of minimizing weight and using the least material possible to control costs, among other factors. To a great extent, when the structure is well proportioned, it will look aesthetic and appealing. From the structural point of view the architectural solu-

tions must utilize and exploit the structure to the fullest extent. In this context, both steel and concrete structures have their own character in expressing the structural system truthfully emerging from the inherent character of the respective materials.

HISTORICAL DEVELOPMENTS OF TALL BUILDINGS: FORM AND STRUCTURE

The tradition of expressing the structure in architectural design begins with the Gothic cathedrals of the middle ages and can be traced into the 19th century with the development of cast iron construction and the theories of Viollet le Duc (1814-1879). In the 20th century, engineers and architects have carried on this tradition with a variety of new forms. Many of the buildings and bridges of the 19th and 20th centuries, which clearly express their structure, have come to be considered as significant works of structural art (Billington, 1983). These structures began to emerge after the Industrial Revolution with the development of a new material: industrialized iron. The Chicago School developed a form of skeleton construction fully consistent with the later ideas of the 20th century. The impressive skyscrapers pioneered in Chicago, have become the dominant architectural elements of the city. This new building type contributed to a new rational understanding of the functions of large city buildings and the technical mastery of steel construction. Not until the 1920s did the technical ideas of the Chicago School gain broad acceptance as form determinants and find new applications in architecture. It was not solely engineers but architects such as Le Corbusier, Mies Van der Rohe, and Walter Gropius, who used new building technologies to develop Modernism as a style.

Simple box-like glass, steel, and concrete buildings, influenced by modernism and the International Style, emerged between the two world wars. Characterized by functionalism and direct expression of materials and structure, modern high-rise office buildings have become corporate icons throughout the world. Buildings are functionally defined by feasible floor areas, building struc-

ture, and the lease span, that is, the core-to-exterior-wall relationships. Modern high-rise structures are typically raised on columns and normally have flat roofs. Their stereometric shapes and structural expression emphasize vertical continuity. The post-modern phase, which followed modernism, is marked by some extraordinary advances in technology, such as new concepts in structural systems (Jencks, 1988).

The Second Chicago School, introduced by Mies van der Rohe and carried on by architectural and engineering firms such as Loebke Schlossman Hackle, Skidmore Owings Merrill (SOM), the early work of Murphy-Jahn, and others, redefined high-rise building design by emphasizing "honest" structural expression. In conjunction with structural integrity, Fazlur Khan created new structural solutions for tall buildings that opened up new and exciting possibilities for tall building design (Ali, 1990). His two internationally famous designs, the John Hancock Center and the Sears Tower in Chicago, demonstrate two different and innovative concepts of structural form – a braced tube system (Hancock) and a cellular bundled tube system (Sears). Both buildings show the structure clearly and represent a reinterpretation of the structural form directly influencing the architectural aesthetic.

The buildings described here are examples of structural art, which embodies three main ideas: efficiency, economy, and elegance. Although all of the buildings described here are functional, efficient, and cost-effective, each of them could have been designed differently.

COMBINING STRUCTURAL FORM WITH ARCHITECTURAL DESIGN

Tall buildings are the most complex built structures since there are many conflicting requirements and complex building systems to integrate. Today's tall buildings are becoming more and more slender, leading to the possibility of more sway in comparison with earlier high-rise buildings. Thus the impact of wind and seismic forces acting on them becomes an important aspect of

the design. Improving the structural systems of tall buildings can control their dynamic response.

The skeleton structure used in modern high-rise construction is the result of the rational use of steel as well as concrete. Among its characteristic features are the reduction of load-carrying members to minimize component sizes and costs and a clear expression of the division between structural and non-structural elements. The skeleton is composed of rigidly connected beams and columns. Steel or concrete frame construction is a particularly suitable form for multi-story buildings. The great strength of modern building materials makes it possible to build taller, to meet today's market-driven demands for efficient use of high-priced urban real estate and maximizing investment returns.

From a purely structural point of view, an optimally designed building must utilize and exploit its structural materials to the fullest extent possible. For a rectangular building, for instance, four massive columns at each corner interconnected by gigantic diagonals can be used to create an effective structural system. However, a system with interior cols in the core area interconnected by closely spaced exterior columns is a better, more efficient structural solution. Other structural alternatives include superframes, telescopic tubes, or a hollow megatube structure (Ali, 1990). Whatever the structural solution is, it must be architecturally functional, efficient, and aesthetically pleasing.

Although there are many structural design alternatives for tall buildings, several steel-framed buildings that exhibit strong structural expression will be presented in this paper. In the following buildings, which present different solutions to different problems, there is significant integration between the structural and architectural design.

LAKE SHORE DRIVE APARTMENTS, CHICAGO (1951)

Mies Van der Rohe's Lake Shore Drive Apartments in Chicago (Fig. 1), originally designed as a resi-

dential prototype soon became an international archetype for the tall modern office building. The twin towers of the Lake Shore Drive Apartments are identical prismatic shafts with recessed loggias at their bases expressing the structural columns of the glass-infilled frame above. The vertical array of metal mullions emphasises the verticality of each tower. The architectural expression of the towers is both rational and ideological. The glass and steel structure expressed in the façade represents an ideal proportional order governed by the constraints of material and technology. (Saliga, 1990). By choosing to use structural steel in his design, Mies was faced with the problem of fire-proofing the exposed structural steel and at the same time expressing the nature of the material from which the structure was formed. To solve this dilemma he conceived an "organic approach to detailing" by developing his vocabu-



Fig. 1 860–870 Lakeshore Drive Apartments,

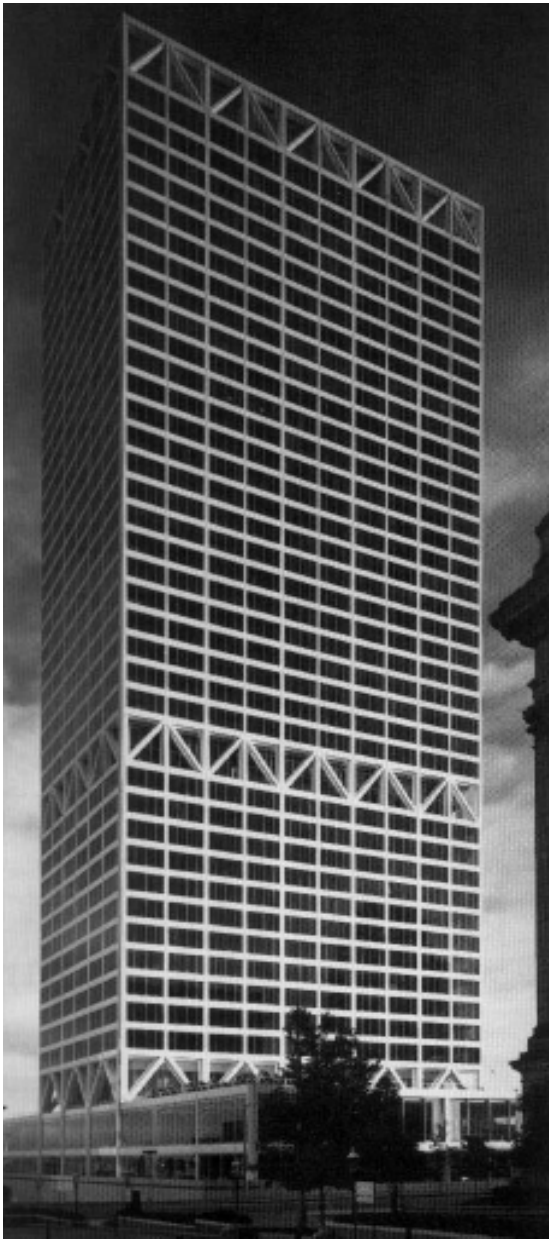


Fig. 2 First Wisconsin Bank Building (now Firststar), Milwaukee, Wisconsin.

lary from rolled steel sections. I-beams, angles, and plates were welded and attached to the formwork for the concrete fire-proofing. As a result, the details revealed the architectural concept and structural intention, as well as clearly ex-

pressed the technological means by which they were achieved (Spaeth, 1985).

FIRST WISCONSIN BANK BUILDING, WISCONSIN (1973)

The First Wisconsin Bank in Milwaukee, Wisconsin (Fig. 2) is a tall office building with an exposed steel frame (Beedle and Iyengar, 1982). The exposed trusses wrapping around the building facades, known as "belt trusses," are at three locations: above the base of the tower, one third of the way up, and at the top. Near the base the truss acts as a transfer structure directing loads from closely spaced columns above to the widely spaced columns below. This transfer structure lightens the base and provides a smooth transition from the lower level to the main building. Widely spaced columns are also desirable at the ground level for marketing aims, where larger bay sizes are required, as well as marking the transition between the base and the tower. The truss within the main shaft of the building also marks a mechanical level. The location of this truss, below the central zone of the shaft seems to strengthen the vertical expression of the tower, rather than breaking it in half. All of the trusses are in the same plane as the rest of the steel frame; however, they are accented by a setback of the building envelope, which occurs only at these levels.

The upper trusses connect the core to the outer columns and transfer some of the wind loads to them thereby reducing lateral deflections and allowing the exterior facades to behave somewhat as a tube. Similar to the trusses, articulated horizontal structural members wrap around the building. The building's small slenderness ratio characterizes its primary vertical expression and is complemented by the horizontal dominance of the spandrels.

JOHN HANCOCK CENTER, CHICAGO (1969)

The fully exposed giant X-braces on the façade of the John Hancock Center (Fig. 3) are its most striking structural features. Completed in 1969, the Hancock tower is a rectangle in plan that

tapers as it rises to its 344-m. height. The main vertical columns and the horizontal ties at the intersection of each X-brace are also expressed. The stereometric shaft rises skyward with few variations. Steel panels in place of glazing indicate each mechanical level. The mullion patterns in the windows change according to the use of spaces in the mixed-used tower. For instance, they are more closely spaced at the residential levels in the upper half of the tower. There is no variation in the structure, so the continuity of the shaft is not interrupted visually. At the top of the tower is another two-storey mechanical level. All of the exposed details of the building are held together by the X-bracing. As a fully integrated expression of form and structure, the braced-tube structure maintains its character of strength and permanence (Ozgen and Sev, 2000; Bennett, 1995).

SEARS TOWER, CHICAGO (1973)

The Sears Tower (Fig. 4) consists of nine equally



Fig. 3 John Hancock Center, Chicago, Illinois.



Fig. 4 Sears Tower, Chicago, Illinois.

sized 22.9-m. square tubes, some of which are cut off at different levels. This expression of each tube's independence is contrasted by the mechanical levels, which are placed at the same level on each tube. Steel belt trusses enclosing these levels wrap around the building, bundling the individual tubes together. The mechanical levels also cap many of the tubes. The barrel-vaulted entrance of the tower (which was added later) is not integrated with the overall structure and the aesthetic intentions of the building. The Sears Tower tapers and steps skyward providing different images from different vantage points as one moves around it in the city. The Sears Tower, because of its large scale and minimalist detailing, is most impressive when viewed from afar whereas the Hancock is more expressive at close range, because the X braces are not as visible from a

distance (Ozgen and Sev, 2000; Ali and Armstrong, 1995).

FIRST EXCHANGE HOUSE (1990)

Catenary arches in compression support this recent example of structural art (Fig. 5). Four large, steel catenary arches, spanning across the two long facades, support the building; the two exposed exterior arches are pulled away from the building allowing the glass curtain wall to be suspended between these arches and parallel interior arches. The floors of the building are also clearly articulated and are tied to the arch by steel beams. A tension tie runs between the ends of the arches. V-shaped braces add stability by structurally and visually tying the building together. Since it is open underneath, the building seems to float behind the supporting arches (Dobney, 1995; Ali and Armstrong, 1995).

HOTEL DE LAS ARTES, BARCELONA (1992)

This 45-story hotel-apartment exo-skeletal tower (Fig. 6) is square in plan and is elevated on a base of columns. The fully exposed structural frame is pulled out from the main building, as in the case of the First Exchange House. The cross bracing is concentrated at the corners. These corners are connected at three separate levels to create a partial trussed-tube form. The attention to details gives the building its visual appeal. The



Fig. 5 First Exchange House, London.



Fig. 6 Hotel De Las Artes, Barcelona, Spain.
(Photographer: David Cardelus)

clear expression of all members and joints allows for interesting shadows and changing views. While the positions of the trusses accentuate the height of the building, the middle truss at a higher elevation emphasizes its top whereas the lower one accentuates its base.

CONCLUSIONS

Expression of structure does not follow any rigid rules, and in many cases different elements of the structure are shown in different ways. For example, one could choose to express all of the spandrel beams by one typical depth regardless of the actual required structural depths. For framed-tubes that transfer loads from closely spaced columns above to widely spread columns

at ground levels, it is possible to choose either a deep transfer girder or let the loads flow through the structural frame in an arch-like manner.

The corner column is an important element in tube structures and special care is taken in the way it is expressed, particularly in its relationship with other columns, spandrel beams, and diagonals. Diagonally braced structures face many design and construction problems that have to be worked out carefully. For instance, where the diagonal is extended to the base, an appropriate pattern must be considered. Consideration must also be given to the manner in which diagonals and other members cross each other and how the tie member is placed as a distinct element from the rest of the spandrel beams. In this context, steel structures have their own character that can be preserved and distinctively emphasized.

In the 21st century it is likely that more and more innovative tall buildings will be built, utilizing the latest technology facilitated by sophisticated structural analysis and cutting-edge construction techniques for high-rise buildings. Tall buildings of the future must be attractive and efficient. Architects and engineers can rise to this challenge if they collaborate and care about people who are the ultimate users of the designs. They must be aware of current trends in the design and construction of tall buildings in order to create realistic and efficient designs. The tall buildings of the future must exploit their structural systems to the fullest extent possible. Architectural expression in tall buildings emanates from the overall building form and its cladding, but structural expression arises from the inherent form of the structural system itself. Whether the building is constructed in steel or reinforced concrete, or a mix of these two materials, uniting structural expression and building form successfully by integrating structural form with architectural design should be the aim of designers of future tall buildings.

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