Hidden Intricacies: The Development of Modern Building Skeletons

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Analysis of structural function can provide insight into the technological development of the skeleton frame.

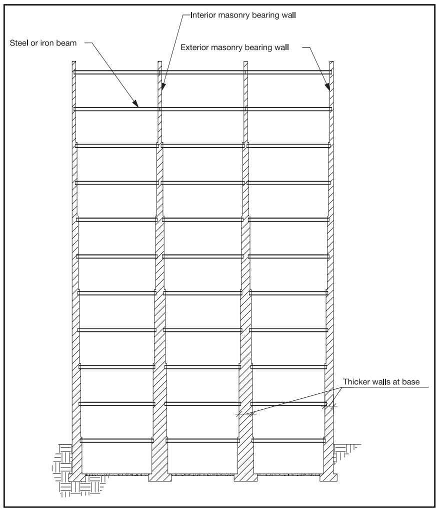

Fig. 1. Schematic cross-section of a pure bearing-wall building. Note that the walls increase in thickness at the lower portion of the building as required by building codes of the 1890s. Drawing by the author.

Introduction

Modern structural engineering began with the Industrial Revolution. There are many examples of structural daring and design expertise in wood and particularly in masonry, but until the introduction of metal framing, materials testing, and numerically based rational analysis made possible long-span beams, complex trusses, and rigid connections, the discipline of structural design remained in the shadow of architectural design. The development of many modern architectural forms depended on the previous or concurrent development of structure: an all-glass wall, for example, was an absurdity until the skeleton frame was an established technology.

Architectural history was shaped as a discipline by the pre-modern development of buildings and therefore by architectural, and specifically aesthetic, concerns.[1] Many examinations of structural evolution in the late-nineteenth and early-twentieth centuries focus on issues central to architectural history: geometry, which for structure means height and the height-to-base ratio called slenderness, and material, which for structure means the introduction of, first, ferrous metals and, later, concrete.

An examination of the evolution of frame construction in the late-nineteenth century is inevitably entwined with the study of early skyscrapers. Unlike many new technologies that are first tested at a small scale and then applied to larger and more prominent uses, modern skeleton frames were first used in tall buildings. There is little reason to build a one-story frame building rather than one with bearing walls, and the distrust of new technology argued against such use. However, the extreme conditions in skyscrapers represented a possible application of a specific technology at a time when that technology was new and developing rapidly.

The era of rapid development was the 1880s and 1890s. At the beginning of this period, all tall buildings had exterior bearing walls; at its end, few did. Examining the technology of tall buildings during the 20 years after 1880 illustrates the introduction and development of steel-framing technology. By using primary examples from one city, the evolution of the types of frames can be illustrated without complications from different building codes. Examples from Philadelphia are used in this paper in keeping with the location of the APT Delaware Valley symposium where this analysis was first presented.

The introduction of engineering into historical analysis of structures is gaining popularity. The typical analysis is reverse engineering, where the design parameters are determined from the object, but can include feasibility study and functional analysis. Justin Spivey has described in detail the fifth project in which the Historic American Engineering Record used engineering analysis as part of a study and report, but the HAER examples focus on bridges, not buildings.[2] Similar analysis of historic buildings is a useful addition to conservation only when it takes into account the often-hidden load paths in building structures.

Part of the acceptance and maturity of a specific technology is agreement among those involved on the meaning of the words and concepts that describe that technology.[3] In examining past developments it is important to make a distinction between the definitions of crucial terms at the time of the development and the definition of those same terms now, not only to avoid stumbling over preconceptions of what the devel-

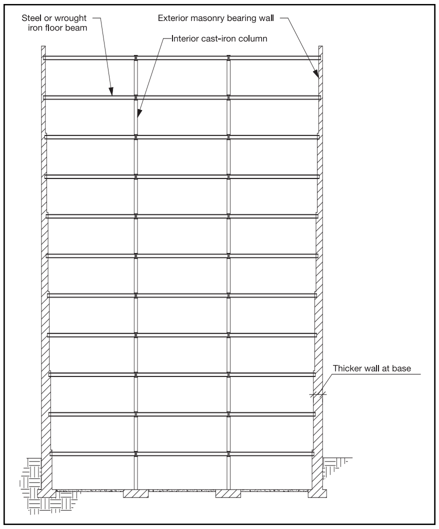

Fig. 2. Schematic cross-section of mixed bearing-wall building. Drawing by the author.

opments actually were but also to gain insight into the differences between what various people thought they were doing and how their accomplishments were viewed afterwards. In the specific case of frame buildings, a complicated situation has been made opaque by changes in the meaning of a few critical words. Descriptions of the buildings — necessary in cases where the actual buildings have been demolished — have often fallen into the trap of assuming that the language has remained static. For example, many contemporary descriptions of the 1884 Home Insurance Building in Chicago have included some variation on the phrase "first to be supported entirely by a steel frame," while examination of the building's physical reality (as recorded during its demolition) and historical context show those nine words to contain at least three errors.[4] The building frame was a mixture of cast-iron, wrought-iron, and steel; it was not the first structure with a significant metal frame; and its exterior wall was self-supporting, which is a significant fact obscured by the use of the modern language. The convenience of modern labels such as "skeleton frame" is based on a common understanding of design and construction techniques that are in use today.

Engineering Functions in Buildings

If we exclude mechanical systems that are needed for a building's useful occupancy but are not necessary for its safe construction and continued existence, there are five engineering criteria for the structure of a building. These criteria — gravity resistance, lateral-load resistance, provision of useful interior floors, enclosure against the weather, and passive fire protection — vary in importance with the building type under consideration but can be said to fairly define a usable structure.

The first two criteria are the most obvious. The first is the ability to withstand the pull of gravity on the building's own weight and the weights of internal occupancy and roof loading, a necessity in maintaining the stability of even such basic structure as the roof of a hut. No useful building of any type fails this criterion, and even the most temporary structures (tents, for example) meet it. On the other hand, the second criteria of withstanding lateral forces is not always so clearly defined. Almost all buildings are capable of resisting some amount of wind or earthquake load, but the proper amount wind pressure to be used in design was not clearly known until the twentieth century, and even today many small buildings (including many single-family houses) are built without an explicit design for the lateral push of code-designated wind pressures. Consideration of seismic force, the other basic lateral load of modern design, did not enter design codes until the mid-twentieth century; current requirements for seismic analysis — including the need for ductile action of structural members, the need for strength beyond the elastic-limit stresses of structural materials, and the need for well-defined load paths — make generic seismic analysis of early frame buildings difficult. Discussion of lateral loads in this paper is therefore limited to wind loading.

The provision of useful interior floors and enclosure against the weather are not required for construction of imposing structures, but few people would refer to the Eiffel Tower or an industrial chimney as "buildings." These criteria therefore emphasize the combination of functional architectural space with structural design. As a side note, the nineteenth-century growth to maturity of structural engineering as a profession began with engineering structures, such as bridges and long-span roofs, and included even purely decorative structures, such as the Eiffel Tower.

The final criterion, protection against fire, is not necessary but has been addressed for centuries through the use of non-flammable finish materials, such as gypsum plaster. It is theoretically possible to ignore this issue and construct a high-rise, steel-frame building with interior floors consisting of wood plank supported by wood joists that span between steel beams. Such a monstrosity has never been built because the need for passive fire protection through the use of non-flammable materials was recognized both in practice and in building codes before the development of the iron frame.[5]

These criteria are found in various examinations of the context and meaning of structural-engineering design. Eduardo Torroja, a mid-twentieth-century innovator in concrete design, listed "to enclose a certain space," "to resist...lateral thrust," and "to ensure... static equilibrium" among various architectural criteria for projects such as providing passages for pedestrians and vehicles.[6] More recently, Bill Addis, an engineer and educator who has written extensively on structural-engineering

Fig. 3. Gladstone Hotel, Philadelphia, during demolition in 1971, showing steel beams spanning between exterior and interior bearing walls. Courtesy of the Library of Congress, Prints and Photographs Division, HABS PA, 51-PHILA, 425-1.

Fig. 4. American Life Building, Philadelphia, during demolition in 1961, showing cast-iron columns (below arrows) in the interior at left and exterior bearing walls. Courtesy of the Library of Congress, Prints and Photographs Division, HABS PA, 51-PHILA, 257-7.

history, stated that engineers "see patterns of loads which the structure must withstand; and they see load paths which conduct these loads through the structure to the foundations and the earth." In the context of historic and mixed structural systems, Addis continued, "it may not even be certain that a structure is carrying these loads by means of one combination of structural actions rather than another. This is especially true of old buildings which will not now be working in precisely the way they were conceived to work…"[7]

An Engineering Typology of Frame-Building Development

Having defined functional criteria, the next logical step is using them to examine development of modern building frames. That development is a key to the origins of both the skyscraper form and most modern construction. Specifically, the first two criteria of gravity and lateral load provide the means to define structure by how it performs in carrying load. This approach stands in contrast to the traditional method of defining structure by materials and form.[8]

Current distinctions between frame and bearing walls are based on current material use. Curtain-wall systems often literally cannot support any significant gravity load — glass panel, light-gauge metal sheet, stucco, gypsum board, etc. Even when using heavier materials that are capable of structural action, such as brick-and-block cavity walls, designers detail them with expansion joints that make vertical-load transmission impossible. Conceptually, designers believe curtain walls to be non-bearing and then make reality fit the belief. Conversely, designers and builders in the transition period may have relied, consciously or not, on the heavy masonry "curtain walls" to resist gravity and lateral loads.[9]

Older distinctions are equally problematic. Research into the use of cast iron continued after wrought iron and steel were first used commercially, and even the promoters of new structural forms had to admit that not all frame buildings met the new ideals. The engineer Corydon Purdy, in describing these ideals, said in 1891 that

> The steel frame of a building ought not to be a mere pile of steel beams and columns. And in the best buildings, especially in the city of Chicago, where the construction of great steel buildings has been rapid beyond all precedent, every detail and every connection is studied, and the whole is braced so completely that the frame may be raised hundreds of feet high, if desirable, from foundation to roof without the aid of a mason's trowel or a carpenter's hammer; a great steel skeleton, strong in its own strength, not only able to carry the direct loads which may be placed upon it, but also able to resist all lateral strains to which it may be subjected.[10]

The qualifier "best buildings" indicates that the conceptual separation of lateral-load resistance from masonry walls was not yet complete, in that the frames might not be properly braced to stand on their own, except in the best buildings. Similarly, old code provisions dictate that wall thicknesses increase linearly with height, while wind forces increase to the second power, suggesting that the codes were written by people with construction experience, not engineers with experience in analysis.[11]

"Skeleton frame" and "cage construction" were two phrases commonly used in the 1890s to describe new buildings. Unfortunately, these terms were variously defined, and the continuing use of "skeleton frame" has created false impressions about the structure of some buildings. Cage buildings intentionally mixed bearing masonry with metal frames, while early skeleton buildings with heavy masonry walls and no expansion joints inadvertently mixed them. Historian Winston Weisman provided what may be the clearest non-engineering definition of cages in a

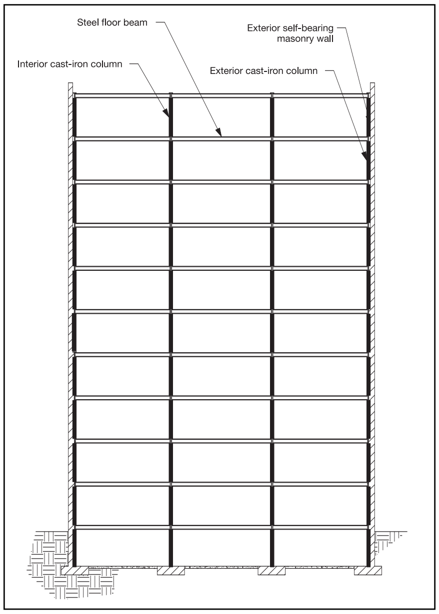

Fig. 5. Schematic cross-section of wall-braced cage building. Note that the walls increase in thickness at a slower rate than in a bearing-wall building and also that the perimeter columns are embedded within the walls at the lower floors but not the upper floors. Drawing by the author.

Fig. 6. Drexel Building. http://en.wikipedia.org/wiki/File:DrexelBuilding_WilsonBrothers_1889Expansion.jpg.

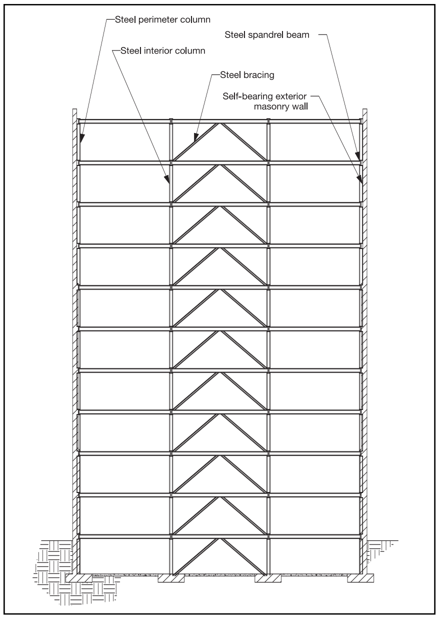

Fig. 7. Schematic cross-section of frame-braced cage building. Drawing by the author.

discussion of George Post's tall buildings: Post "preferred 'cage construction' in which the outer walls supported themselves while the floor and roof loads were held up by an interior metal frame."[12] This definition, however, does not address lateral-load resistance, which is necessary to a structural understanding of any building.

The core of function-based analysis is definition of the loads that buildings carry. In addition, the distinction in engineering design between live (occupancy) and dead (structural) loads can be safely neglected for this discussion: there are no ordinary building structures that carry live load without dead or vice versa. This assumption leaves three distinct load types: the combined dead and live loads of the interior floors and the roof, the weight of the exterior enclosure walls, and the lateral force of wind on the exposed building faces. Two notes are required for clarification: first, the interior floor load added to the exterior wall load is taken as the total weight of the building; second, interior walls are not broken out as a separate type of load because they were present only in some buildings, while every building has an exterior wall.

The first type, the pure bearing-wall building, can be described as one in which all of the floor loads and exterior-wall loads are carried vertically by the walls in compression and lateral wind loads are carried by the walls in shear (Fig. 1). The second type, the mixed bearing-wall building, is one in which a substantial portion of the floor loads (at the perimeter), the exterior-wall loads, and the lateral wind loads are carried by the walls and a portion of the floor loads are carried by interior columns, usually cast iron (Fig. 2). The Gladstone Hotel, completed in 1890 at the corner of Pine and 11th streets in Philadelphia, was a good example of a pure bearing-wall building, with its steel beams and tile-arch floors supported on multiple parallel brick bearing walls (Fig. 3). The American Life Insurance Building, completed 1895 at Walnut and 4th streets, shows mixed bearing-wall construction, with interior cast-iron columns and a brick-and-stone exterior bearing wall (Fig. 4).

Chronologically, the next development after the use of iron framing for floors and interior columns was the use of complete iron frames to support all of the interior floor loads. In this third type of structure, columns at the perimeter of the building were variously located inboard of the wall, embedded in the interior face of the wall, or placed near the center of the wall thickness, but they lacked attachments to the wall that would allow for transfer of vertical loads. In a building of this type, the floor loads are carried by the metal frame, the exterior wall supports its own weight, and the wind loads are carried by the exterior walls in shear. References to masonry piers "reinforced" with iron columns show that the gravity load was still thought of as the main issue driving structural design.[13] It is of critical importance that the materials of construction are not important to the analysis, as long as they were functionally adequate to withstand the applied loads; this structure type includes buildings with cast-iron, wrought-iron, and possibly steel columns, as well as both brick and stone walls. The building type with a complete frame surrounded by a self-bearing wall is called a "cage" in the literature of the time and by Weisman; the type described here is called a wall-braced cage to distinguish it from the next type to be discussed (Fig. 5). The Drexel Building of 1888 at 5th and Chestnut streets had a complete frame of steel beams and cast-iron columns supporting ten stories over its 142-by-220 foot plan. The exterior columns were embedded within the self-supporting brick exterior wall (Fig. 6). Gravity load so dominated engineering thinking for building frames that there is little evidence of lateral-load analysis or design for bearing-wall buildings and barely more for wall-braced cage buildings.

Fig. 8. Hotel Walton, Philadelphia, 1964. Courtesy of the Library of Congress, Prints and Photographs Division, HABS PA, 51-PHILA, 269-1.

The fourth type, the frame-braced cage, followed shortly after the introduction of wall-braced cages (Fig. 7). The two cage types look similar, but the frame-braced cage has the distinguishing feature of some form of lateral bracing in the metal frame. The bracing took various forms that all continued to be used with skeleton frames, including cross-bracing, moment connections between girders and columns, and portal frames with columns and beams built up continuously of plates and angles. Moment frames — either portals or ordinary beams and columns with moment connections — had to be made of wrought iron or steel because they require the rigidity of connection that only hot-driven rivets could provide at the time. Diagonally braced frames could possibly be built safely with cast-iron columns because the bracing forces, in theory, did not create tension or moment in the columns. In practice, frame-braced cages were built with wrought-iron or steel columns. The Hotel Walton of 1895, a neighbor of the American Life Building at Broad and Locust streets, had a complete steel frame with its exterior columns embedded within the self-supporting brick exterior wall (Fig. 8).

A short description of a frame-braced cage is that the frame carried the floor loads and the lateral wind load, while the exterior walls carried only their own weight. In engineering terms, a frame where the masonry carries load is not a skeleton. Gerald Larsen and Roula Mouroudellis Geraniotis came close to describing this idea when they said that “a modern skeletal frame . . . is entirely self-sufficient and independent of its masonry enclosure.” They go on to support this statement with four reasons based on the gravity load of the wall and a fifth concerning lateral stability of the frame, showing a logic similar to that suggested here. Curiously, they apply this logic to the Home Insurance and its predecessors, buildings which, as a group, are not independent of their masonry enclosures.[14]

The difficulty of using simple terms to describe these buildings can be seen in the *Sanitary Engineer*’s 1889 description of the Drexel Building. The magazine’s structural review included a description of the iron frame and also the phrase “all the walls are essentially curtain walls, sustaining no other load than their own weight.”[15] This is, of course, not the current definition of curtain

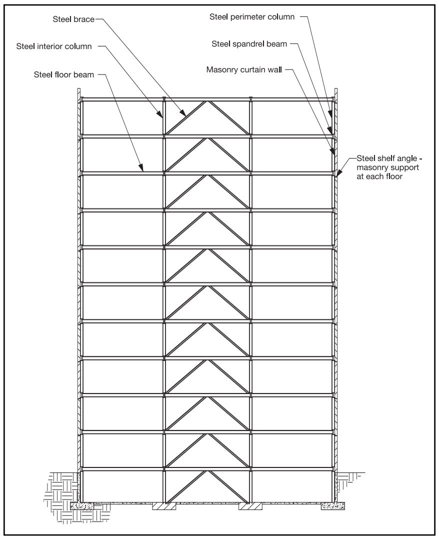

Fig. 9. Schematic cross-section of skeleton-frame building. Drawing by the author.

Fig. 10. John Wanamaker Store, Chestnut Street elevation, 1973. Courtesy of the Library of Congress, Prints and Photographs Division, HABS PA, 51-PHILA, 370-1.

wall. The *Sanitary Engineer*'s definition — a curtain wall is any wall that does not carry floor loads — was used elsewhere at that time. For example, the New York City Building Code of 1892 required "curtain walls . . . supported wholly or in part on iron or steel girders" to be thicker at the bottom of the facade than at the top. This provision is nonsensical unless the code's authors assumed that the curtain walls are carrying loads from their tops to the foundations.[16]

The final development in distributing loads within a frame was the development of recognizably modern skeleton frames, where the wall is supported at every floor (or sometimes every other floor) by a frame that has lateral bracing. The frame carries the floor load, wall load, and lateral load, and the exterior wall has been reduced to one function — enclosure (Fig. 9). This type of structure is the most familiar today, as it represents the norm in multiple-story building construction; the 1900 John Wanamaker Store at Market and Chestnut streets is a good example of a very large (255-by-490-foot plan, ten stories) building with a skeleton frame and masonry curtain wall (Fig. 10).

The examples given so far are straightforward and can easily be categorized. On the other hand, the Chicago Stock Exchange, completed in 1894 to a design by architects Adler and Sullivan, has a mixed system (Fig. 11). The street facades were supported by the steel skeleton, while the rear lot-line wall carried its own weight but not that of the floor framing.[17] Such a building is defined as a skeleton frame by structural logic: if the self-supporting rear wall were removed, it would have no effect on the structural stability of the building but would only expose the interior to weather.

In summary, structural forms can be defined using load criteria as follows:

1. A **pure bearing-wall** building is one in which all floor weight, all wall weight, and all wind pressure are carried by the masonry walls.
2. A **mixed bearing-wall building** is one in which a significant amount of floor weight, all or nearly all wall weight, and all wind pressure are carried by the masonry walls.
3. A **wall-braced cage building** is one in which the floor weight is carried by a metal frame, while the wall weight and wind pressure are carried by the masonry walls.
4. A **frame-braced cage building** is one in which the floor weight and wind pressure are carried by a metal frame, while the wall weight is carried by the walls.
5. A **skeleton-frame building** is one in which all floor weight, all or nearly all wall weight, and all wind pressure are carried by a metal frame.

Nearly all skeleton frames were steel. Significant amounts of cast-iron columns were used in bearing-wall and wall-braced cage buildings. Wrought iron appears most frequently as floor beams in forms other than skeleton frames and as columns in structural cages. Frame-braced cages and skeleton frames are the focus of another discussion regarding the designers' intent.

Intended Designs and Accidental Structure

The categorization method used here is based on how buildings were intentionally designed. An engineer who used truss analysis to design diagonal braces expected that the truss model accurately reflected the distribution of stresses in the building. However, a modern analysis might include a comparison of the relative stiffnesses of the exterior walls and the braced frame. Since wind forces are transferred to the building frame from the outside walls subjected to wind pressure, the frame in a building where the walls are stiffer than the frame might never be stressed by wind.[18]

None of the buildings of the period of interest had expansion joints in the modern sense: straight vertical and horizontal joints ran through the entire thickness of a curtain wall to permit independent movement of various portions of the wall. In addition, the thicker a masonry wall is, the greater its structural capacity to handle stresses (such as those created by thermal movements) that are less than those created by full-building lateral and gravity loading.

Statements in various sources suggest that engineers were intentionally mixing the structural capacity of masonry and steel. Regarding the 1892 Venetian Building on East Washington Street in Chicago, the historian Joseph Siry cites Corydon Purdy, one of the pioneers of structural engineering in building design as saying that the "steel frame's bracing [resisted] 70 percent of the remaining pressure, and the interior partitions 30 percent."[19] However, it is unclear exactly what Purdy meant, since the apportioning of lateral load between a steel frame and masonry shear walls would be extremely difficult using the portal and cantilever analysis methods available in the 1890s. The Venetian had a steel skeleton frame and a supported exterior wall; the frame was braced by both portal frames and diagonal rods. The interior partitions were lightweight materials, such as terra-cotta tile. Such partitions would be incapable of resisting any significant load, such as 30 percent of the wind pressure on a 13-story building. A likely explanation is that the portal frames resisted 70 percent of the lateral load, and the diagonal rod bracing, contained within partitions, took the remainder.

The relatively thick masonry walls used with pre-1900 skeleton frames are capable of carrying both vertical and lateral loads. While it is unlikely that designers attempted to apportion load

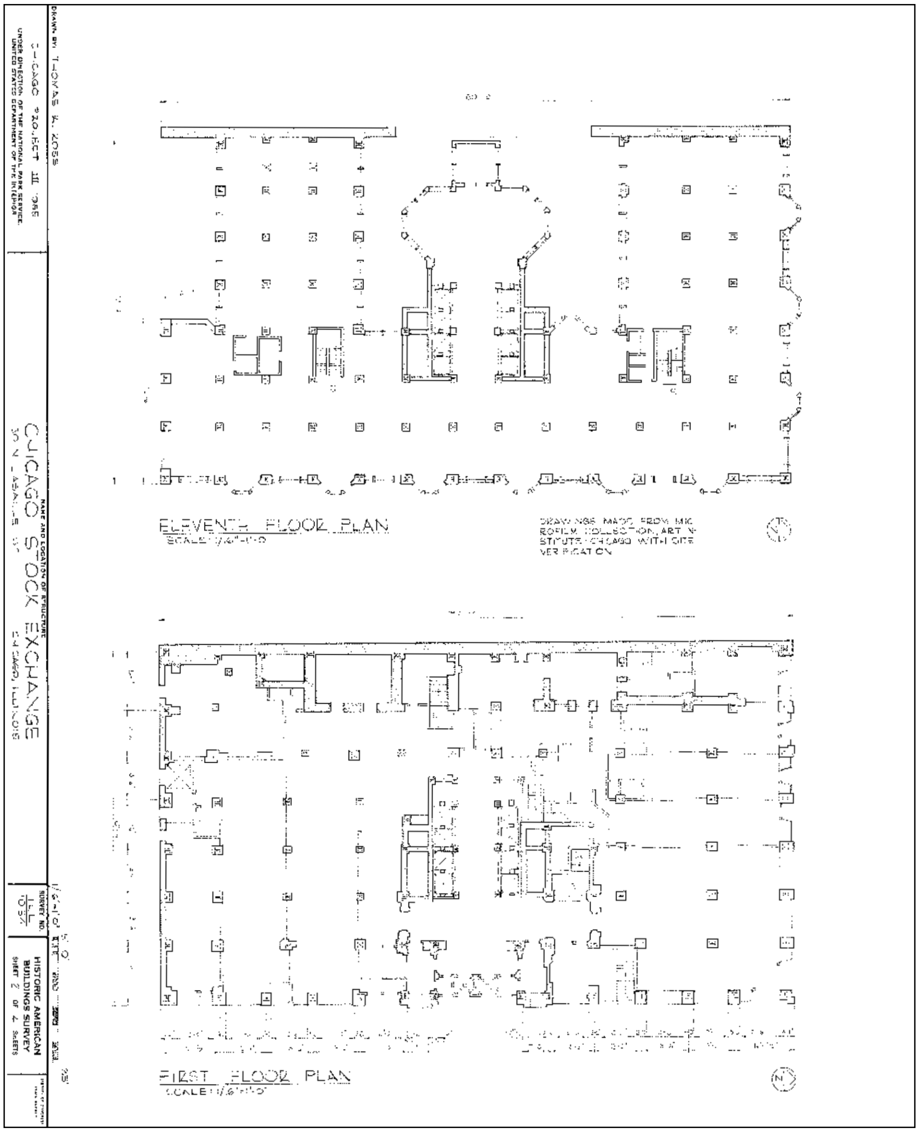

Fig. 11. Chicago Stock Exchange, floor plans. Note the thick west wall, which was self-bearing. Courtesy of the Library of Congress, Prints and Photographs Division, HABS ILL, 16-CHIG, 36.

between steel and masonry, it is almost certain that some of the walls are carrying load. The in-plane stiffness of the masonry spandrel panels is often greater than the stiffness of the spandrel beams that support them, and the stiffness of the walls as a whole is often greater than that of the frames. The tight construction typical of the period, where the spandrel columns are encased in masonry piers built integrally with the wall and where the facades are in close contact with the spandrel beams, ensures load transfer back and forth between frame and wall. Such unintentional load transfer can be eliminated only through the use of facades incapable of resisting load and/or fastened in a manner that prevents the transfer. The post-1950 construction of the glass curtain wall is an example of the first, while the post-1960 use of expansion joints that were properly spaced and sized is an example of the second.

Alteration and Preservation

The issues involved in altering or repairing nineteenth-century steel, wrought iron, and cast iron are well known, but the issues involved in changes to the overall systems are not. For example, a skeleton-frame building — even one with a 20-inch-thick exterior wall — can have any section of wall removed without affecting structural stability. However, tall buildings without expansion joints may have built up considerable compression in the walls through inadvertent bearing-wall action, and this possibility must be taken into account in sequencing removals.[20] Each of the frame types create distinct problems during restoration and alteration analysis and construction.

Bearing-wall buildings are obviously dependent on their walls for both lateral stability and gravity support, but incremental changes to the walls may result in situations where inadequate amounts of wall remain for lateral resistance. In other words, storefronts at the first floor or large windows at upper floors may have been installed one at a time, with no single alteration being large enough to trigger a lateral-load review. In cases like this, the architect, engineer, or contractor who first notices the issue may well wish it had gone undiscovered, as an owner or tenant proposing a minor change such as installing a single side-wall window is not going to take responsibility for or pay for an overall lateral-load repair. There is little useful guidance from statutory sources, as building officials and codes are focused on new construction. Even sources intended for renovation, such as the International Existing Building Code, may not help, as their guiding principle is to allow existing non-conforming structure, as long as proposed work does not make the situation less safe. This constraint implies that in a situation where the existing lateral-load resistance is inadequate for code loads, no alteration that further reduces the capacity — such as cutting a window into a bearing wall — may be made.

Even if the existing lateral-load capacity is adequate, creating new wall openings is problematic, as the new framing should be designed to replace the lateral-load capacity of the portion of wall to be removed, which is always more new structure than the simple lintel most building owners expect.

Damage to the exterior walls of bearing-wall buildings, such as material deterioration to masonry or cracking from differential foundation movement, must be treated as damage to the base structure, rather than as facade damage. Both structural and facade damage are potential life-safety hazards, but structural threats may require more drastic actions, up to vacating buildings.

Wall-braced cage buildings are the most problematic type, since they have the same reliance on their exterior walls as bearing-wall buildings but may appear to investigators in the field or in written descriptions as "frame buildings." Discrepancies in field data — such as columns that are visible at the upper floors but not at the lower floors or "skeleton-frame" buildings with cast-iron columns — are often indications of a cage frame. Cage-frame and mixed-bearing-wall buildings combine the problems of altering or repairing heavy masonry bearing walls with the problems of altering or repairing cast-iron columns.

Frame-braced cage buildings and skeleton-frame buildings are stable in an overall sense if portions of wall are removed, but they may have thick walls that can be difficult to properly support with new lintels. Buildings of these types from the nineteenth century suffer from the reverse problem as bearing-wall buildings: people may have mistaken them for buildings without metal frames and supported alterations (such as mezzanines or new stairs) on the masonry walls. For this reason, a current-day professional who knows that the walls were originally intended to not carry gravity load cannot assume that the walls still carry none.

Conclusion

The analysis outlined here provides a method of separating changes in architectural form from changes in structural paradigm. Between 1870 and 1900 tall buildings were built in Second Empire, American Renaissance, and Chicago styles, among others. These style changes had little to do with the underlying structure. In 1952 historian Carl Condit claimed that the relatively unornamented Chicago Style was "associated with the invention and mastery of steel framing."[21] Since then, that connection between style and structure has been modified and debated in various ways, but the widespread construction of heavily ornamented, skeleton-frame buildings shows that the connection is a philosophical, not a physical, one.

The development from bearing walls to skeleton frames is therefore a decades-long story of incremental changes: the introduction of iron interior columns, the introduction of buried iron-spandrel columns, the change from cast-iron to ductile-metal columns, the addition of bracing between the columns and the beams, and the design of the spandrel columns and beams to carry the weight of the masonry. This gradual evolution was created by the work of many people in New York, Chicago, Philadelphia, and elsewhere.

The development of frame technology entailed a series of individual changes in the physical construction of buildings, each change being more sophisticated than the last in terms of structural theory, and each more subtle than the last in terms of physical presence:

- the distinguishing change between all-masonry bearing-wall buildings and the bearing-wall and interior-column mix was the substitution of iron columns for interior bearing walls and masonry piers.
- the distinction between bearing-wall buildings and wall-braced cages was the addition of exterior columns buried in the walls.
- the distinction between wall-braced and frame-braced cages was the addition of bracing between columns and beams.
- the distinction between frame-braced cages and skeletons was the detailing of the masonry-to-spandrel-beam connections.

Each change was less visible than the one before.

Engineering analysis can address the various arguments made about early skyscrapers and proto-skyscrapers.[22] A statement about early modern skyscrapers can be correlated to skeleton-frame buildings; one about early tall buildings not constrained by the structural limitations of masonry can include both skeleton frames and structural cages; and one about tall buildings using (some) modern technology can include skeleton frames and both types of cages. This level of detail allows insight on the history of architectural and engineering practice at the end of the nineteenth century and on the introduction of new technology in the building trades.

Present-day issues revolve around preservation and use. Many early skyscrapers still exist, and nearly all are considered historic. Many are designated landmarks. Design professionals and contractors are still learning how to deal with these buildings, which present different and often more complex problems than the houses, churches, and small-scale structures that were the focus of early preservation efforts in the United States. Unlike houses (often converted to museums), churches, and national monuments, tall urban buildings survive through commerce. Their continued use and continued existence depend on the ability of owners, architects, and engineers to analyze life-cycle maintenance and repair costs. Ironically, buildings that contain structural technology that represented a break with the past will rely on historians' work to survive.

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Notes

1. For examples, see David Watkin, *The Rise of Architectural History* (Chicago: Univ. of Chicago Press, 1980), 34–41.

2. Justin Spivey, "Engineering Methods in Historical Research," *Cultural Resource Management* 23, no. 4 (2000): 35–38.

3. For a description of this process, see Thomas Kuhn, *The Structure of Scientific Revolutions*, 2nd ed. (Chicago: Univ. of Chicago Press, 1970), 128.

4. David Handlin, *American Architecture* (New York: Thames and Hudson, 1985), 122.

5. Frank Brightly, *A Digest of the Laws and Ordinances of the City of Philadelphia* (Philadelphia: Kay and Brother, 1887), 351. See also *Laws Relating to Buildings in the City of New York* (New York: The Record and Guide, 1887), 492.

6. Eduardo Torroja, *Philosophy of Structures*, trans. J. J. Polivika and Milos Polivika (Berkeley: Univ. of California Press, 1958), 3.

7. Bill Addis, *The Art of the Structural Engineer* (London: Artemis London, 1994), 12.

8. For example, Winston Weisman, "A New View of Skyscraper History," in *The Rise of an American Architecture*, ed. Edgar Kaufmann, Jr. (New York: Praeger Publishers and the Metropolitan Museum of Art, 1970), 119–122.

9. Randolph Langenbach, "The Seismic Strengthening of the Woodrow Hotel, Oakland," in *The Seismic Retrofit of Historic*

Buildings, ed. David Look (San Francisco: Western Region of the Association for Preservation Technology, 1991), 16-1–16-25.

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