Building Code Enforced Evolution in Early Skeleton Buildings

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INTRODUCTION

One of the great technological changes of the nineteenth century was the introduction of skeleton framing as the common method of supporting large buildings. Skeleton frames, which use a system of columns and beams to support a building's interior floors and exterior walls, turned previous logic on its head: masonry walls were reduced in importance from the element that carried all structural loads and defined buildings' appearance and construction quality to decorative weather screens with no structural purpose. Unlike most technological improvements, the new materials and systems were introduced on a large scale, in the tallest and most structurally-challenging buildings of the day, rather than being tried and developed on a small scale first. In the United States, several distinct structural types were in use simultaneously in the 1880s and 1890s, each with its own advantages and disadvantages, and each with a group of supporters among the real-estate, design, and construction communities. This paper examines the influences of structural costs in the evolution of the different types.

Construction cost is only one factor that influences structural design decisions. Life-cycle costs, aesthetic choices, space programming, and reliability may outweigh construction cost. For all of these factors, perceived value is used in the decision-making process rather than actual value, so that the use of cast iron declined simultaneously with the rise of perceived safety problems, even though the actual safety provided by the material did not change.

It is not clear that technological superiority played a role in type decisions. New technology, and building technology in particular, may be in use for years or even decades before its weaknesses become apparent. Three structural types are examined: masonry bearing-wall buildings, which represent the pre-existing technology in 1880; "cage-frame" buildings combining bearing walls and cast-iron columns, which are representative of the 1880s and 90s; and skeleton-frame buildings using steel columns, which became representative of the twentieth century. Using modern structural criteria, skeleton framing is the best system, but this conclusion is based on over a century of testing and examination of buildings.

Unlike most industrial-technology commodities, buildings are not standardized products. Every building is created by hand labor from relatively small standardized units of construction materials. As a result, it is difficult to compare actual buildings of different structural types because other cost-influencing differences (e.g., finish quality and extent of mechanical services) are present.

Theanalysis here therefore takes two parts: detailed cost analysis of the structural systems of three idealized building models, and comparison of the costs of actual buildings representing all three types on the basis of dollars per square foot of floor area. Other cost comparisons have been used for buildings, particularly cost per cubic foot of enclosed space, but since space is typically rented or sold on a square-foot basis, this is the most direct comparison.

CONTEXT

American construction in the late nineteenth and early twentieth centuries was dominated by small, local firms acting as general contractors, providing labor for some building elements (most often masonry) and sub-contracting others. Materials were a mix of locally- and nationally-produced, low- and high-tech items of varying industrial sophistication. The production of steel, cast iron, and brick are of interest to discussion of structural costs. There are significant costs associated with five processes for each material: (1) creation of the material, including rolling of steel beams, sand-casting of iron shapes, and molding, cutting, and firing of bricks; (2) fabrication for specific use, including cutting steel shapes, drilling and punching of rivet holes in steel, and shop-riveting of connection pieces; (3) shipping to the destination, specifically transportation (typically by railroad) from the fabrication or creation plant to the city where the building is located; (4) hauling to site, specifically local transportation of the material from a freight terminal to the construction site, typically by horse wagon; (5) erection, specifically lifting materials into position using cranes or hoists and then final placement and connection. The importance and cost of these processes varies with the material in question: steel requires all five, while there is no difference between creation and fabrication for cast iron; the amount of erection labor per pound of brick is greater than the amount per pound of steel, making erection costs for brick more important for the total cost. All of these costs can be represented on a per pound basis, combining labor and material costs. This is natural form of costs for shipping and hauling, but is used here specifically to even out discrete element differences for the other processes. Masonry costs can be easily converted between per-pound and per-brick, but since steel is erected piece by piece, only the per-pound cost can be directly compared.

Creating steel sections was the largest-scale and most advanced industry of the three. The largest concentrations of steel companies were near Buffalo, Pittsburgh, Cleveland, and Chicago, and the combination of Carnegie and Federal Steel (the two largest companies in 1900) with others to form United States Steel, with roughly two-thirds of domestic production, took place in 1901. (Serrin, p. 122) By contrast, cast iron was locally produced by relatively small companies, such as the Architectural Iron Company in New York. This difference can be directly related to the manufacturing process: the development of steel technology gradually changed from batch to continuous production, and economies of scale in converting iron ore to steel and in rolling specific cross-sections were exploited in steadily larger mills; iron pieces were inherently cast one at time, and a larger factory could only cast more pieces simultaneously without necessarily gaining efficiency. In addition, creating casting molds required highly-trained artisans, while machinery-driven steel production could used semi-skilled laborers. (Morison, p. 186)

Cast-iron columns were ready for use once casting was complete, since connection brackets were cast integrally with the columns shafts, but steel straight from the mill consisted of simple sections that required fabrication to be usable. Because steel pieces in a building were of different lengths and required different rivet holes, there were few economies of scale to be had in cutting and hole-punching, and fabrication tended to be concentrated in companies that used skilled labor and were smaller than the mills.

Brick production gradually evolved from a local hand-craft industry to a national industrialized one, but with an important split. The most highly skilled laborers and most advanced production techniques tended to be used for face brick, to ensure uniform quality, size, color, and texture, while less effort was put into the common brick that made up the bulk of the masonry used. Masonry materials, therefore, were often a mix of locally-produced low-tech products and nationally-produced, heavily industrialized products.

The most visible element of construction, on-site erection of fabricated materials, was generally resistant to industrialization. The different geometry of every building, differing geometry within a given building based on architectural design and structural member sizes at different floors, steadily changing materials supply paths during construction, and the much larger tolerances in construction than those used in machinery all made hand-assembly necessary during erection. The last item in particular required skilled laborers: unlike the precision fit common in factory production of machinery, size and location tolerances in construction were as large as half an inch, and assembly typically required resequencing or additional forcing effort such as pulling on a partially-erected frame with guy wires to make parts fit.

The first cost of a material or assembly is not necessarily the driving factor in its use. As Ranko Bon described in his analysis of construction costs:

> First, the minimization of any component of building costs does not guarantee that total costs will be reduced, let alone minimized. For example, a reduction of construction costs may result in an increase of maintenance and replacement costs that offsets the initial savings. Second, and even more important, both costs and benefits should be taken into account. For instance, an increase in construction costs may result in an even greater increase in benefits associated with building utilization.
>
> (Bon, 1989, pp. 15-16)

A clear example of the second type of benefit is the elimination of interior bearing walls in the cage and skeleton types, allowing far more flexibility in space utilization than was possible in bearing-wall buildings. A less obvious but still important example would be the use of thinner exterior walls in the skeleton type, increasing both the rentable square footage and the amount of daylight admitted through windows. Not only was there more space to be rented, the space was of higher perceived quality.

BUILDING TYPES

Three building types are to be examined in detail: bearing wall, cage frame, and skeleton frame. Because all three building types include steel beams carrying fire-resistant floors, all represent late-nineteenth century building technology. The introduction of new building materials and systems based on the mechanization of mines, foundries, and mills began in the United States in the 1830s with cast-iron columns and by 1900 included mass-produced wrought-iron, steel, brick, terra cotta, and primitive reinforced concrete.

Common Features

The three construction types share common features which will not be analyzed as they do not differentiate the types but are described for an understanding of the buildings. These features are floor construction, windows, mechanical systems, and interior finishes. The elements analyzed in detail – the building frame and the exterior walls – provide a means to support the floors against gravity, brace the building against lateral wind loads, and create the basic separation between the outdoors weather and the interior controlled climate, but do not provide usable interior spaces. The purpose of the common elements described here is to complete the building for use.

One of the most prominent building-technology advances in the nineteenth century was the development of practical “fireproof” floors. While no material is capable of resisting the heat of fire for an indefinite period of time, the combination of wrought-iron or steel beams carrying and encased within terra-cotta tile arch floors was capable of both carrying heavy loads and withstanding fire tests to the standards of both the late nineteenth century and current codes. (Freitag, pp. 58-60) These floors entered common use in the 1870s and remained popular until the 1910s. All three building types described in this paper use the same combination of steel floor beams supporting tile arch floors.

All three types are assumed to have the windows (wood sash with single glazing) that were in common use before 1900. The size of the windows, three feet wide by five feet high and spaced at six feet on center, creates a wall that is 25% window and 75% solid, which is typical for masonry-wall construction of that era. The bare structure of tile-arch floors, exterior walls, and interior columns would be finished with plaster ceilings, plastered terra-cotta partitions, and wood flooring. While the amount of plaster varies slightly, the bulk of the finish work is identical for all three types.

Mechanical systems in the 1890s consisted of plumbing, steam heat, and either electric or coal-gas lighting, regardless of structural type or building use. Elevators were typically low-speed direct-current electric or (more rarely) steam-power hydraulic.

The models of all three types used in analysis are meant to represent a typical 1890s New York building on a mid-block lot. Such buildings have blank side walls facing adjoining lots, an ornamented street facade, and a plain rear facade facing a small yard. The effect of differing building codes is discussed in “Location Specificity” below.

Bearing-Wall Building Type

The defining feature of the pure bearing-wall building is that all gravity loads are carried by masonry walls down to the foundations. That definition can be used for masonry buildings thousands of years old, so that several other features must be defined for the type as it was in use in large multi-story buildings in the late nineteenth century: (1) interior and exterior walls are solid brick, except for any ornamentation applied to the surface of the street facade, (2) interior bearing walls have multiple openings to permit passage from one portion of the building to another, but do not have rooms larger than one inter-wall segment, (3) the floor construction is standard “fireproof” terra cotta on beams supported by the walls.

By 1880, this type was becoming obsolete for large buildings. The presence of interior bearing walls broke up the usable floor space into strips roughly twenty feet wide, which could be acceptable in residential buildings where the space was inevitably broken for individual tenants, but was awkward for commercial or industrial use. A mixed bearing-wall variation on this type, where the interior walls were replaced by rows of cast-iron columns and steel girders, had a relatively short period of use, as it was superseded by the cage type.

Cage Building Type

Cage buildings consist of a frame – most often cast-iron columns supporting wrought-iron or steel beams – that carries the weight of the interior floors and roof and is surrounded by self-supporting masonry walls. The gravity loads are split between the frame and the walls, while the walls provide stability against lateral wind load. The use of columns and girders to carry the floor beams eliminates the interior bearing walls and allows for thinner exterior walls.

In retrospect, the cage building type is a hybrid, combining features of bearing-wall and skeleton buildings, but this was not apparent at the time. Cage building were originally used as a method of introducing the new technology of cast-iron columns in such a way as to reduce dependence on heavy masonry walls, and were often referred to as “frame” buildings in a way that suggested the later developments of skeleton framing. Since cage construction appeared as early as 1880, it could not have been foreseen that it was a transition to the skeleton type that did not yet exist.

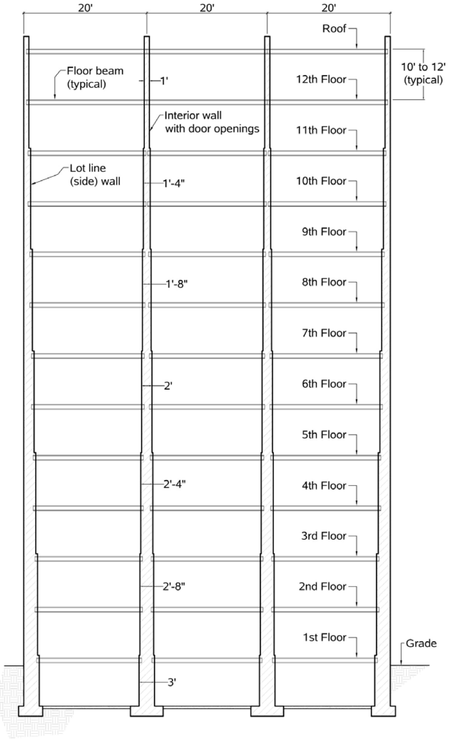

Figure 1. Transverse section of a bearing-wall building. Note that floors and interior partitions are not shown for clarity, and that the walls are 12 inches thick at the top and increase 4 inches for each two floors.

Figure 2. The Gladstone Hotel (1890) in Philadelphia: bearing walls and steel beams visible after demolition of floor arches and an outside wall. (HABS/HAER http://memory.loc.gov/ammem/collections/habs_haer/)

Skeleton Building Type

In skeleton buildings, all loads are supported by the steel frame, including the floors and the exterior masonry wall. The wall is typically carried at each floor by a hung lintel – a steel shelf angle supported by the exterior beams at each floor. Because the wall is not capable of providing any structural support, the frame has to be designed for both gravity and lateral loads. The non-load-bearing wall (a "curtain wall") can be a constant thickness the full height of the building.

Steel skeletons were developed in the 1890s and became the dominant structural form for large buildings in the United States by 1900. This form remains a common method of supporting tall buildings in large part because it is conceptually simple and relies on proven steel technology.

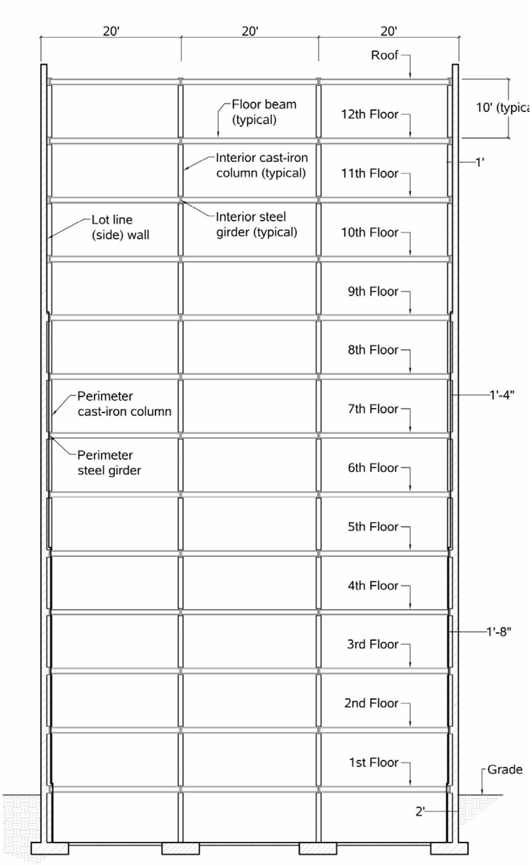

Figure 3. Transverse section of a cage-frame building. Note that floors and interior partitions are not shown for clarity, and that the walls are 12 inches thick at the top and increase 4 inches for each four floors.

Figure 4. The Divine Lorraine Hotel (1894) in Philadelphia, a typical cage building. (HABS/HAER http://memory.loc.gov/ammem/collections/habs_haer/)

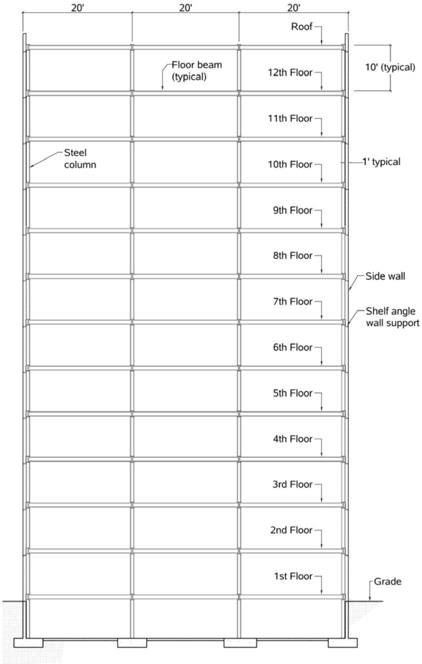

Figure 5. Transverse section of a skeleton building. Note that floors and interior partitions are not shown for clarity, and that the walls are 12 inches thick top to bottom.

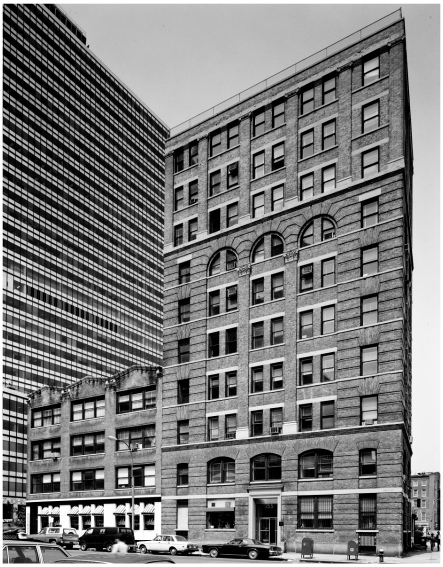

Figure 6. The Matheson Building (1897) in New York, a typical early skeleton building.
(HABS/HAER http://memory.loc.gov/ammem/collections/habs_haer/)

Technology Comparison

With hindsight, the skeleton-frame building is seen as one of the great inventions of the late nineteenth and early twentieth century. This form of construction allowed for rapid erection of buildings, flexible interior layouts free of immovable walls, and facades that could be built of different materials with any degree of fenestration. The ductility of structural steel provides a high level of safety against accidental overload and the destructive effects of high winds and seismic motion. These advantages, however, were not necessarily clear to designers and builders in the 1890s who had to choose between competing systems.

Steel construction technology was first developed by engineers in bridge and railroad projects and was foreign to most architects and building contractors. Building construction, on the other hand, had long been dominated by architects and master craftsmen in the traditional materials of wood and masonry. The transition period of 1880 to 1900, when all three building types were in use, is marked by the contrast between engineered skeleton-frame buildings and rule-of-thumb bearing-wall and cage buildings. Engineers objected to this situation on the basis of safety, with an editorial in the *Engineering News* saying

> Good engineering has tended away from cast-iron columns during some years past, even for low buildings, and their use for buildings higher than five or six stories has been

> regarded by nearly all competent structural engineers to be doubtful practice at best. Yet they have been very generally used in light tier-building work for much greater heights...
>
> ("Structural Engineering in Apartment House Construction", 1904)

The low opinion of structural engineers for cast-iron columns and, by extension, the cage type, was in part based on two well-publicized collapses, the Ireland Building on 3rd Street in 1895 and a soap factory on Twelfth Avenue in 1897. ("Fall of a Building with Cast-Iron Columns", 1895, & "The Collapse of a Portion of a New Building in New York City" 1897) Forensic analysis of these failures indicated that the exterior walls gave insufficient lateral bracing to the frame, particularly during construction, making catastrophic collapse of the entire building possible. Engineers judged the skeleton frames to be inherently safer because the frame was stable by itself, without contributions from the masonry. Designers did not completely switch from cages to skeletons until a third fatal collapse – the Darlington Apartments in 1904 – made continued use of cast iron in tall buildings anathema in the building community. ("The Collapse of the Darlington Apartment House in New York City,", 1904 & Starrett, 1928, p. 41)

Location Specificity

In the United States, separate building codes were enacted by various cities during the nineteenth and early twentieth centuries. The applicable provisions of the New York code – increasing wall thickness with height for bearing-wall construction, lesser increases with height for cage and skeleton buildings, higher allowable stresses for steel than cast iron in column use – are contained in varying forms in the codes of other major cities. In addition, pre-1900 buildings ten stories and taller were concentrated in a handful of cities (New York, Chicago, Philadelphia, Boston, and St. Louis) with advanced codes.

Material and labor prices varied from city to city, but less so than the difference between the prices in cities and in small towns. All of the major cities were within several hundred miles of steel foundries and brick plants, all had local cast-iron industries, all were on main-line railroads. All had labor supplies that fluctuated with the national economy.

Ultimately, the lack of regional variations in structural type can be shown empirically: all of the cities where tall buildings were constructed before 1900 had representatives of all three types. However, there is a distinct difference between the 1880s and the 1890s: in the earlier decade, significant numbers of tall buildings were constructed only in Chicago and New York. Since the 1880s were dominated by bearing-wall buildings and had no skeleton-frame buildings, the bearing-wall and cage types are better represented in those two cities than in the others. (Landau and Condit, pp. 111, 148-149, 157)

RELATIVE COSTS

In order to compare costs, a schematic model of each building type was designed per the New York 1892 code to provide material quantities. This code prescribed masonry wall thicknesses based on building height, width and internal geometry, and provided allowable stresses for steel and cast iron design. The floor loads used meet code standards for office or residential occupancy. The design is simplified from actual conditions – for example, the beams required to make floor openings for elevator and stair shafts are not included – but this type of omission affects relatively small amounts of the structure; these models are equivalent to schematic designs at the beginning of a project, specifically meant as a method to choose between differing schemes.

All three models are a 12-story, 60-foot wide by 80-foot deep building, constructed on a mid-block lot with one street facade and two blank lot-line side walls. Buildings of this size were constructed in all three types between 1880 and 1900, although the bearing-wall type was rare after 1885 and the skeleton-frame type was rare before 1895. The prices are typically those of 1899.

Steel costs are arrived at by totaling the weight of steel called for in each design. The typical 20-foot-span floor beams are the same for the three designs, while the girders in the cage and skeleton designs are different and steel columns are only present in the skeleton design. The cost of the cast iron columns in the cage scheme comes from the volume of metal in the columns, multiplied by the density of the iron, and multiplied by the cost per cubic foot. Brick costs are similarly derived from the volume, with an additional step to convert from bricks to pounds: a single common brick and its associated mortar joints measures 8 inches long, 4 inches deep, and one-third of 8 inches high. This allows for conversion of cubic feet to brick count at a rate of 20.25 bricks per cubic foot; a similar conversions accounts for the amount of mortar in the wall. Table 1 is a summary of the basic structural cost calculations, based on data from "The Building Trades: Material Market;" (Gillette, 1906, pp. 266, 527); "The Ton-Mile Rate and a Great Consolidation;" "The Milwaukee Classification and Price List of Castings;" "The Cost of Steel Structures;" "Fluctuations in the Price of Iron and Steel"

Table 1: Costs of Selected Structural Elements

	Bearing-wall Building Cost		Cage Building Cost		Skeleton Building Cost	
	Model data	Unit costs	Model data	Unit costs	Model data	Unit costs
Number of bricks	1648 350		877 500		607 500	
Material per brick		$0.05810		$0.05810		$0.05810
Fabrication per brick		$0.00000		$0.00000		$0.00000
Shipping per brick		$0.00178		$0.00178		$0.00178

	Bearing-wall Building Cost		Cage Building Cost		Skeleton Building Cost	
Hauling per brick		$0.00148		$0.00148		$0.00148
Erection per brick		$0.00600		$0.00600		$0.00600
Total cost per brick	$0.06736		$0.06736		$0.06736	
Total masonry cost	$111 033		$59 108		$40 921	
Floor-beam steel (lbs)	349 440		513 505		718 870	
Material per pound		$0.02000		$0.02000		$0.02000
Fabrication per pound		$0.00500		$0.00500		$0.00500
Shipping per pound		$0.00120		$0.00120		$0.00120
Hauling per pound		$0.00025		$0.00025		$0.00025
Erection per pound		$0.00325		$0.00325		$0.00325
Total cost per pound	$0.02970		$0.02970		$0.02970	
Total floor beam cost	$10 378		$15 251		$21 350	
Column cast iron (lb)			163 376			
Material per pound				$0.03000		
Fabrication per pound				$0.00000		
Shipping per pound				$0.00000		
Hauling per pound				$0.00025		
Erection per pound				$0.00325		
Total cost per pound			$0.03350			
Total cast-iron cost	$ 0		$5 473		$ 0	
Column steel (lbs)					314 559	
Material per pound						$0.02000
Fabrication per pound						$0.01250
Shipping per pound						$0.00120
Hauling per pound						$0.00025
Erection per pound						$0.00325
Total cost per pound					$0.03720	
Total steel column cost	$ 0.00		$ 0.00		$11 701.59	
Total for structure	$121,411.22		$79,832.59		$73,973.23	

There are two categories of costs: type-dependent and type-independent. Both are included in the total building cost data given in Table 2, but the detailed analysis includes only the type-dependent costs that can influence builders' decisions. Type-independent building elements include terra-cotta floor construction, interior plaster and partitions, wood flooring, roof membranes, windows, elevators, stairs, plumbing and plumbing fixtures, and coal-gas or electric lighting. While the number and speed of elevators would vary depending on the use, there was little differentiation of elevators in the nineteenth century compared to the twentieth. One aspect of the type-dependent wall construction is type-independent: architectural ornamentation. The sizes of the brick walls used in the analysis are the minimum required by the building code, implying a building with no architectural ornamentation on its street facade, which is not realistic for the era, but is justified by the equal cost of ornament for all three types.

In order to place the structural costs in their context of the total building cost, Table 2 contains square-foot costs for actual buildings that were comparable in size to the structural type models, excluding land costs. The twelve buildings in this group were those constructed in New York in 1898 and reported in the *Real Estate Record and Guide*, the leading real estate journal of the era. Two other buildings listed in the *Record and Guide* are omitted because during their construction they were substantially changed from their published size. The second group in the table consists simply of the total cost of a model building at various square-foot prices, while the third group is the square foot structural costs of the three model buildings.

Table 2: Square-Foot Building Costs ("Big Building Operations in 1898")

Building	Floors	Base Area (square feet)	Total Cost (dollars)	Cost ($/gross square ft)	Use
85-89 Liberty Street	14	12 350	450 000	2.60	Office
110-116 Nassau Street	12	15 400	250 000	1.35	Office
3-7 Wall Street	10	3 286	450 000	13.69	Office
298-300 Broadway	10	5 280	110 000	2.08	Loft
302 Broadway	14	5 500	350 000	4.55	Office
396-398 Broadway	10	4 900	250 000	5.10	Office
729-731 Broadway	12	5 400	175 000	2.70	Loft
105 East 15th Street	10	4 500	150 000	3.33	Apartment
115-120 West 34th Street	12	7 200	500 000	5.79	Hotel
145-147 Fifth Avenue	12	4 050	275 000	5.66	Loft
140 Fifth Avenue	12	4 480	425 000	7.91	Loft

Building	Floors	Base Area (square feet)	Total Cost (dollars)	Cost ($/gross square ft)	Use
539-545 Fifth Avenue	13	11 325	750 000	5.09	Hotel
Generic building	12	4 800	115 200	2.00	Undefined
Generic building	12	4 800	172 800	3.00	Undefined
Generic building	12	4 800	230 400	4.00	Undefined
Generic building	12	4 800	288 000	5.00	Undefined
Model bearing-wall structure only	12	4 800	121 411	2.11	Undefined
Model (cage structure only)	12	4 800	79 832	1.39	Undefined
Model (skeleton structure only)	12	4 800	73 973	1.28	Undefined

COST ANALYSIS

There is some uncertainty regarding the total building costs given in Table 2, since they represent not known costs but rather the costs as reported for publication by various individuals. Architects, contractors, and owners may have reason to overstate or understate costs in different circumstances. Two known factors may contribute to the exceptionally high stated cost per square foot of 3-7 Wall Street (also known as 84 Broadway), both related to construction logistics. This building entirely filled an L-shaped lot, meaning that no staging area was available, and the two adjacent streets were among the most congested in the city at that time. Cart access, transfer and storage of materials, and erection must all have been constrained to a high degree even for work in New York. These factors may not be enough to explain the high cost, but they at least provide some guidance. There is no known reason why 110-116 Nassau Street should have been so much less expensive than other buildings; the structural costs as discussed below suggest that the stated total cost is incorrect.

There are substantial differences in the non-structural portions of buildings constructed for different uses. Loft buildings typically have plain interiors, with no few or no partitions and little plumbing. Office buildings typically had a set of partitions dividing the interior into individual rentable spaces and, since they were designed for higher occupancies, larger bathrooms. Apartment houses had more partitions to divide the interior into rooms, relatively more plumbing, and a relatively higher-quality level of finish. Finally, high-end hotels had the most partitions and plumbing, to divide the interior into many small rooms each with its own bath, and high-quality levels of finish. These differences are not clearly represented in the twelve examples from 1898, as the average loft cost is $4.59 per square foot, the average office cost is $5.46, the one apartment cost is $3.33, and the average hotel cost is $5.44. The lack of correlation for apartment use and cost may be related in part to location-based logistics, as it was easier to perform construction in the less-dense residential neighborhoods than in the congested commercial and manufacturing districts.

Given that the basic structural costs vary from $1.28 to $2.11, the lowest cost building possible would seem to be a skeleton-frame loft building, where the cost would be $1.28 plus the costs for the fireproof floors, interior finishes, roofing, windows, stairs, elevator, and small bathrooms. 298-300 Broadway apparently represents this minimum, suggesting that the minimum cost of non-structural elements is approximately $0.80.

The average building cost is $4.99, so structural costs as calculated represent 26 to 42 per cent of the average total buildings cost. All other costs being held equal, switching from bearing-wall to skeleton construction results in savings of $0.83 or 17 percent of the total. That is the largest structural cost savings possible, but the savings in switching from bearing-wall to cage construction is 14 percent and from cage to skeleton construction only 3 percent. In other words, an owner or builder accustomed to pricing bearing-wall buildings could get most of the possible savings by switching to cage construction, while someone using cage construction would gain little by switching to skeleton construction.

These costs are comparable to those expected in 1899: J. Hollis Wells, an architect in New York, was quoted as having erected a steel-frame building in 1898 for 32 cents per cubic foot and expected to complete another in 1899 for 34 cents per cubic foot (assuming 10 feet floor-to-floor, $3.20 and $3.40 per square foot); George Hill, a structural engineer, was quoted as expecting steel prices to vary between 8 and 15 per cent of total construction cost, depending on building use and assuming skeleton construction. ("Is the Price of Structural Steel Checking Building?") Wells's cost estimate agrees with both the actual buildings listed and the estimated total construction costs for the models. Hill's estimate implies steel costs between 40 and 75 cents for $5 per square foot total costs; the model skeleton building steel cost is $33,051 or 57 cents per square foot.

CONCLUSIONS

Looking only at cost, there was a strong economic incentive to switch away from bearing-wall construction to either cage or skeleton construction. When skeleton frames were first introduced, their exterior masonry walls were the same thickness as those used on cage buildings. As designers and builders began to take advantage of the skeleton type in the late 1890s and early 1900s, the walls used on skeleton buildings were gradually reduced to the 12-inch code-proscribed minimum thickness. The cost difference of cage and skeleton frame buildings was small, while the difference between both frame types and bearing wall construction was significant. The switch from cage to skeleton construction is difficult to explain on economic grounds, but relatively straightforward when other considerations are included. The growing distrust of cast-iron columns in the 1890s could only be addressed by switching from cage to skeleton framing.

One way of looking at the type evolution is that a relatively small volume of steel replaced a large volume of brick, which was a direct reflection of the high strength-to-weight ratio of steel and the low ratio for masonry. Regardless of material and fabrication costs, this gives steel construction an edge in shipping, hauling, and erection costs, simply on the basis of less material being transported both horizontally to the site and vertically within the site. If steel erection required much more labor than masonry construction, this savings would be reduced, but the reverse is true: steel erection typically proceeded more rapidly than masonry because it did not require good weather, did not have to be timed around the setting of mortar, and could use inexpensive semi-skilled laborers for all jobs but riveting.

In addition, the substitution of roughly 600 000 pounds additional steel for 6 000 000 pounds of brick with meant that the total cost became less sensitive to per-pound material cost fluctuations. Another reason that steel use was insulated from material price fluctuations was the cost of fabrication: base material cost for steel columns was only 54 per cent of the in-place material cost, with fabrication as the second largest cost, while base material cost was 86 per cent of in-place masonry cost. Because fabrication and erection was done by relatively small local companies and not the large steel producers, those costs were fairly stable over time.

Ultimately, the change in technology use represented by the three building types was influenced by a combination of architectural design, structural safety, and cost. The successively lower costs of the newer types allowed the designers and builders investigating the new technology and the owners paying for the buildings to make their decisions on the basis of functionality and safety without incurring additional costs.

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