Early Predictions of Steel-Frame Deterioration: Permanency in High-Rise Construction

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ABSTRACT: The possibility of corrosion reducing the life-span of steel-frame buildings was recognized during the first construction of such buildings in the 1890s. The same designers who worked on the early steel-frame buildings stated publicly that this issue was a concern, but made no long-term effort to study the problem. After a 1903 report that steel at one such building was in good condition after five years in service, there was little discussion until facade failures from corrosion became a concern in the 1970s.

INTRODUCTION

Steel-frame skeleton construction had critics, like all new technologies, from the time it was first used and discussed in the 1890s. Some of the criticism came from knowledgeable sources and was based on sound logic: steel framing was neither good nor bad simply because it was new or because it enabled high-rise construction, and architects, engineers, and contractors who worked with steel framing were capable of judging it on its expected performance. Load capacity was a straightforward matter of structural design, but long-term performance could only be addressed through speculation, since no such buildings had been constructed before. In New York and Chicago, the two cities with the largest collection of pre-1930 steel-frame buildings, facade-inspection laws introduced after 1980 and the subsequent repair campaigns have revealed extensive corrosion damage to spandrel beams and exterior columns. Critics of steel framing had explicitly predicted this form of damage before 1900.

Among architect critics, George B. Post stands out for his practical knowledge of steel framing. Post was a New York-based architect whose work included the bearing-wall Western Union tower; the partial-frame Produce Exchange, World, and Havemeyer Buildings; and the skeleton-frame Sprague, Vincent, and St. Paul Buildings, all constructed in New York between 1884 and 1899 except for the 1872 Western Union. In 1895, Post stated in the *New York Times* an opinion he had previously discussed in professional journals: the common practice of erecting steel-frame buildings with their exterior columns embedded in the facades was dangerous in the longer term. He believed that the columns could not be inspected once the masonry was in place, and that one or two wythes of the masonry provided insufficient fireproofing to protect the columns against the heat from fires in adjoining buildings and insufficient waterproofing to protect against long-term exposure to the weather. Post ultimately argued against the use of steel framing in the form that was common in his time, and for the use of steel in combination with heavy exterior walls. Post□s comments echoed those of a number of contemporary engineers.

In 1903, the five-year-old Pabst Hotel in New York was demolished to clear its site for subway construction. This provided an opportunity for the building community to observe the ordinarily-hidden frame, and, as was reported in the engineering press, the steel was found to be in good condition and was scheduled for re-use in a new building. The issue of corrosion faded from discussion until masonry failures in the 1970s triggered extended inspections of old high-rise facades and their supporting steel. Corrosion was found to be prevalent at corner columns, roof-level spandrel beams, and spandrel beams supporting water-tables or balconies, although it could occur anywhere on the facades. In short, the problem predicted in the 1890s was real.

PREDICTING ENDURANCE

Knowledgeable observers raised many concerns in the early days of skeleton-frame skyscrapers, ranging from the most basic issue of whether tall steel-frame buildings were stable to the prediction that adjacent streets would become hopelessly over-crowded. The structural fears were addressed by a combination of empirical performance (no tall building collapsed as a whole) and the efforts of architects and engineers to provide reasoned responses. This did not mean that the concerns were necessarily wrong as, for example, New York's existing street-congestion problems were made worse by the concentration of tall buildings in the downtown business district. The same professionals who designed and built tall frame buildings addressed in writing and through their buildings the various concerns that were published in both popular and trade journals.

Among the nineteenth-century professionals who stated doubts regarding the longevity of steel framing, several were prominent in promoting the same technology: George Post, an architect originally trained in both architecture and engineering who designed several of New York's tallest buildings in the 1880s and 90s, and the engineers William Sooy Smith, William Birkmire, William Freyer, and Joseph Freitag. All promoted steel-frame technology in their work, either intentionally or by example, and all expressed their opinions in print. Birkmire, Freyer, and Freitag published books in the 1890s with architects and builders as the target audience describing the new technology of steel-frame buildings. Post was particularly conflicted on the construction of tall steel-frame buildings, and spoke against their construction despite having designed tall buildings in New York since 1870. (Landau 1998, p. 110) In 1902, Post designed the Main Building for City College of New York with stone and terra cotta bearing walls, retreating from the technology he had helped to popularize in the previous years. (Landau 1998, pp. 131-135; Gray 1992).

In an interview with the *New York Times* in 1895, shortly before the completion of his 25-story high St. Paul Building in lower Manhattan, he expressed his concerns in so blunt a manner that the full headline read "Limits of High Buildings – Views of Mr. Post, Personally Opposed to Sky-Scraping Structures. – The Dangers That Threaten – Long-Continued High Winds and Exterior Fires Might Be Disastrous – Commercial Height 300 Feet [91m]." (n.a. 1895) In the interview, Post stated that he was "personally opposed for many reasons to the construction of high office buildings" and then went on to describe his reasons: (1) long-term winds might cause side-sway with "oscillations [increasing] with each swing;" (2) steel columns built into the exterior walls "are removed from all possibility of examination;" (3) columns built within the exterior walls may be subject to thermal expansion and warping during fires in adjoining buildings; and (4) the steel frame may corrode. While the specifics of his logic may not exactly match forensic analysis of building failures over the intervening century, each point agrees with known problems revealed since his time.

The first issue, increasing side-sway under constant load, is today known as one possible effect of resonance, which is rarely found in buildings under wind load but has been observed in bridges under wind load (e.g., the collapse of the Tacoma Narrows Bridge in 1940) and in buildings under seismic load. When a structure is subjected to a cyclical load with a frequency near the natural frequency of the structure, the resulting stresses and deflections may far exceed those caused by a similar-magnitude static load. However, as Post himself described, engineers were learning to brace frames to reduce sway (and therefore damp out the potentially destructive movements), and the load from wind is too small and its period too dissimilar relative to the stiff, heavy masonry-walled buildings of Post's era for resonance to take place.

The second issue, the inability to see spandrel columns built within exterior walls, has proven to be a problem particularly when combined with the issue of steel-frame corrosion. Ordinary maintenance on high-rise buildings did not include removal of portions of the exterior walls until the post-1980 facade-law inspections so the exterior faces of these columns were rarely seen, and the interior spaces abutting the columns are occupied office or residential space with plaster finishes so the interior faces were rarely seen.

The third issue, the possible effect of fire, has been more of a problem inside steel-frame buildings than outside. Fire spread from building to building was more prevalent when all buildings had wood-framed floors. The introduction of new technology both in construction (e.g., terra cotta and other "fire-proof" floors) and in fire-fighting (e.g., high-pressure hydrants and automatic sprinklers) in the late nineteenth century reduced building-to-building fire spread.

The fourth issue, the possibility of a gradual reduction in strength of the frame from corrosion of the steel, was long forgotten but has proven to be the most serious problem Post mentioned. Waterproofing in early steel-frame buildings was commonly a coat of paint, and the curtain walls were mostly solid masonry with no internal waterproofing or means of directing water flow. As a result water may remain within the masonry for long periods. Post was at his most prescient when he was asked if "the grandsons of engineers now living [will] appreciate the dangers" of old buildings damaged by corrosion. His response was that

> I think they will. These great buildings are not likely to come to pieces without giving competent engineers ample warning, by cracks in the stonework or settling of beams, or some other sign of instability. The determination of causes for such defects rests upon principle which never change, and therefore will be equally as good warning to our descendants as to ourselves.

Smith was a bridge designer, but helped popularize steel over wrought and cast iron through his work. His experiences with maintenance and repair of steel bridges led him to a conclusion that was as grim as the worst possibilities Post had discussed: in 1902, Smith said that if building columns corroded at the same rate as truss members in railroad bridges then high-rise buildings would become unsafe within twenty years of their construction. For this reason, he was opposed to complete skeleton frames that supported the exterior walls. (Fleming 1935)

Birkmire, on the other hand, did not give a lengthy discussion of his opinions on the long-term deterioration of steel. Instead he paraphrased the arguments of those who believed that corrosion was a serous problem, such as "The constructors and producers of cast-iron....claim that rust honeycombs and eats entirely through" wrought iron, but also stated that "The objection to wrought-iron or steel on account of rusting may seem more real, and yet we have seen pieces of wrought-iron beams, anchors, etc., taken from very old walls unharmed by rust." (Birkmire 1894, p. 17-18) While he did not clearly state his opinion on this topic, he did quote an unnamed author in the journal *Architecture and Building* as saying that "There are really but two questions [regarding tall buildings] seriously demanding consideration – the proper protection of the steel frame against elements of danger, decay and fire, and the obstruction of the light from surrounding properties." He also quoted an article in an unnamed newspaper as saying that "Another constant menace to these buildings is from corrosion. The steel frame is embedded in masonry, where it cannot be examined, and after a few years no one can tell what condition it is in." (Birkmire 1906, p. 31, 106) This may well have been an indirect quote or paraphrase from Post, who had said in the New York Times interview that steel columns "when built into the walls are removed from all possibility of examination without tearing the building." (n.a. 1895)

Freyer discussed steel framing in 1891, at the same time that the first skeleton frames with curtain walls fully supported by steel or wrought-iron beams were being constructed, by comparing the corrosion resistance of cast iron and steel:

> Some constructors advocate the use of cast-iron as the only material for columns of skeleton structures. When columns are built around with brick work they are permanently buried out of sight. Between the columns and the outer air there are only a few inches of masonry work, through which dampness or rain finds its way. In wrought iron this is insidious, and it honeycombs and eats entirely through the metal. Mild steel, such as riveted columns, are made of, rusts faster than wrought iron at first, than slower. Cast iron, on the contrary, oxidizes on the surface in damp situations; rust does not scale from it, and the oxidation formed is of a much less dangerous kind....Advocates of riveted steel columns insist that such columns, when properly encased in fireproof and waterproof materials, as the intent always is that they shall be, are protected permanently from injurious influences. High buildings are erected for permanency, to last for centuries. Years from now the question will be practically determined whether skeleton structures are a wise or foolish method of building, whether they are stable and lasting, or secure and reliable for only a comparatively short number of years. (Freyer 1898, pp. 477-478; Freyer 1891)

While this seems similar to Birkmire's reluctance to give an opinion, there is an important qualification in the quote: steel columns are safe only if "properly encased" in waterproof materials. Freyer also proposed the use of a higher-than-normal safety factor for steel columns, based on an assumption of material loss.

Freitag gave the most explicit discussion of longevity, in a section called "Permanency of Skeleton Construction" in the "Skeleton Construction" chapter of his book *Architectural Engineering*. This section is worth examining at length, as it summarizes the state of knowledge in the 1890s. The first paragraph describes the "considerable discussion" in the context of a building boom using steel framing and the "great importance" of the issue. This paragraph comes to a conclusion since confirmed, which is that the designers and builders of the era relied on "faith in such combinations of materials" given "the want of reliable data under present conditions." Since the problem was one that would take time to present itself, there was simply no way for anyone then to know the answer.

Freitag went on to discuss the mechanism of corrosion, and specifically the effect of lime mortar or other compounds that would create acidic conditions, and the difference between weathering (with changes in temperature, humidity, and external pressure) and foundations which are in permanently wet but unchanging conditions. He promoted the use of portland cement or cement mortar as corrosion protection for steel exposed to static conditions, such as those in foundations, and states that lime mortar should not be used in any location where it would be exposed to both steel and wet conditions. He also explicitly states that masonry is not waterproof and will therefore not provide protection to steel. Freitag came to the final conclusion that all steel must be carefully and thoroughly coated with paint. He dismissed the idea that the cohesion between iron and concrete would allow an impervious coating of cement by pointing out that

> in building work a perfect union between the cement mortar and metal-work can never be attained at all points, [so] a thorough coating of paint must largely be relied upon. All constructive ironwork should, therefore, be well coated with either lampblack mixed with oil, or red lead and linseed-oil....A careful inspection of all painting, both at the shop and in the field, should be rigidly enforced. (Freitag 1895, pp. 50-53)

Freitag's recommendations echo those of the New York building codes. As there were no national building codes in the United States until after 1900, the period of steel-frame development was influenced most heavily by the local codes for the large cities where tall buildings were constructed, most notably Chicago and New York. The provisions in the local buildings codes requiring masonry or concrete encasement of exterior-wall steel are ambiguous, in that they serve as both fire- and water-protection. The requirements that steel be painted, while representative of good practice in a general sense, are more obviously water protection, since the paint provides no protection against heat. The 1892 New York City code required a coating of "oxide of iron and linseed-oil paint before being placed in position, or coated with some other equally good preparation or suitably treated for preservation against rust." Interestingly, Freitag specifically recommends against the use of oxide-of-iron paint on the grounds that it does not adhere well to steel, high-lighting his point that more long-term performance data was required. (Freitag 1895, p. 53) The 1901 and 1916 codes were less specific about the reason, but merely required “All structural metal work shall be cleaned of all scale, dirt and rust, and be thoroughly coated with one coat of paint.” (Cosby 1908 p. 231; Cosby 1922 pp. 105-6) The 1916 code is of interest because it was the first modern building code in New York and remained in effect (with numerous amendments) through 1968. By comparison, the pre-1900 building codes in Chicago and Boston did not require paint, but only solid masonry fire-protection. (Freitag 1895, pp. 50-53)

After 1924, the publication of a national steel code by the American Institute of Steel Construction led to the migration of language regarding the protection of structural steel away from the local codes. This was not inherently a problem and the steel code has included provisions for painting steel, but the division of building codes into sections and separate references for each material had the effect of deflecting attention from interactions between materials and systems. The steel code, no matter how will written, has never provided more than minor references to masonry. The paint provisions have been relatively simple, requiring for example one shop coat of paint and touch-up paint in the field for all steel not encased in concrete. (n.a. 1941)

Finally, not everyone foresaw dangers. An engineering article published in Britain in 1901 used less than one page to describe the structure of high-rises, compared to more than thirty pages describing mechanical systems. The comfort of tenants was discussed, longevity of buildings was not. (Bolton 1901) Birkmire quoted a discussion of ridiculous claims made against skyscrapers from the *Architecture and Building* article, such as the assertion that pendulum clocks were affected by building side-sway, as a method of dismissing claims in general. (Birkmire 1906, p. 20)

THREE BUILDINGS, CIRCA 1900

The 1899 St. Paul Building in lower Manhattan was one of George Post’s last skyscrapers and it clearly shows his conservative approach to protecting the exterior steel columns. The building occupied a small, irregularly-shaped lot and was 25 stories and 94m high, making it briefly one of the tallest buildings in the world. The structural system of the building was typical of the era in broad terms, with a steel framing supporting the masonry curtain walls and interior floors, but the details were designed to protect the columns. First, the columns were set entirely inboard of the curtain wall, so that water would have to penetrate the entire thickness of the wall before it could touch column steel. The spandrel beams carrying the wall were supported by brackets that effectively were cantilevered extensions of interior floor beams, and the columns were waterproofed by a combination of a solidly-grouted space between the steel and the terra-cotta fireproofing and asphalt-impregnated felt applied to the painted steel. Figures 1 and 2 show the relation of the wall to the steel framing in section and plan. In theory, the terra cotta and grout could be removed to permit inspection of all faces of the columns (or at least, those portions which were standing free outside of the floor structure) but there is no record of such inspections ever being performed. (Birkmire 1906, pp. 189-191; Mujica 1929, pp. 29, 59)

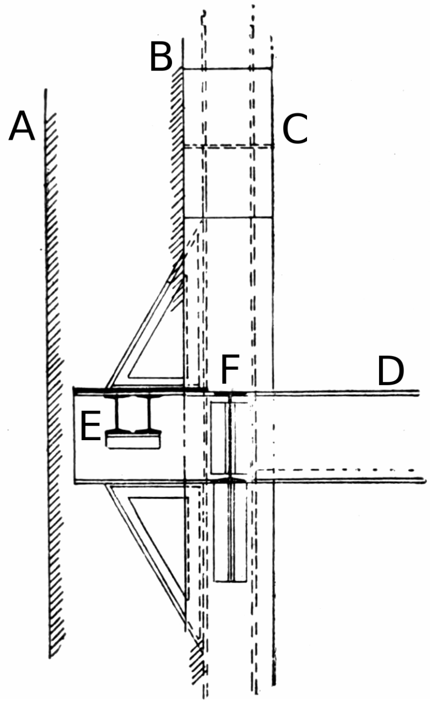

Figure 1: Exterior wall section of the St. Paul Building, showing the exterior (A) and interior (B) faces of the exterior wall, the spandrel column (C), an interior girder (D), the wall-carrying double spandrel beam (E), and the frame spandrel (F); (Birkmire 1906, p. 190)

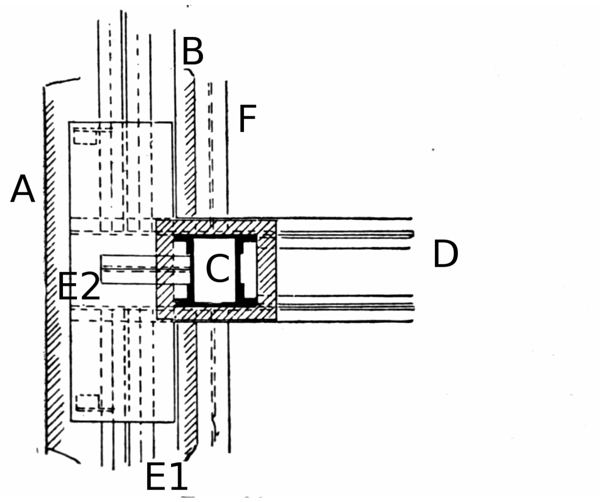

Figure 2: Exterior wall plan section of the St. Paul Building, showing the exterior (A) and interior (B) faces of the exterior wall, the spandrel column (C), an interior girder (D), the wall-carrying double spandrel beam (E1), the bracket to carry the spandrel beams (E2), and the frame spandrel (F); (Birkmire 1906, p. 190)

Despite Post's claim that his system provided "more effectual exclusion of moisture and prevention of corrosion, superior fireproofing, and a connection of the floor-system so as to avoid eccentric loading of columns." it was not widely copied. The bracketed connections required more material and more rivet-driving labor than ordinary beam-to-column connections and therefore were more expensive, the interior position of the columns used up otherwise rentable floor space, and, perhaps most importantly, there was no general consensus among real estate developers and building owners that the corrosion problem even existed.

The 1898, nine-story Pabst Hotel was much closer to average than the St. Paul in everything except its location: the combination of the diagonal path of Broadway and Manhattan's street grid creates a number of small triangular blocks, such as the one between Broadway, Seventh Avenue, and 42nd Street where the Pabst was located. The building had the steel frame, brick curtain walls, and patented floor system that are typical of era, and is only now of interest because of a report issued after its demolition. The first New York subway, the Interborough Rapid Transit, began construction in 1900 on a route that ran west under 42nd Street and then curved north onto Broadway. In order to construct the curved section of track under the triangular block, the IRT company purchased the hotel and demolished it in 1903. In the interest of addressing the corrosion issue that was still active in the design community, if not among building owners, The *Engineering News* published a report of the conditions exposed as demolition progressed. The report directly addressed the issues that had been discussed in theory a few years earlier: "The entire structural part of the building is in excellent condition, in fact it seems fully as good as in a newly-built building. Of greatest interest is the condition of the steelwork. This is excellent throughout, in the columns as well as the beams, the surfaces still show the original adherent coat of black paint, and there is no indication of deterioration by corrosion..." (n.a. 1903) This report provides empirical evidence to fill the gap in data that Freitag had discussed eight years earlier, unfortunately in a what can now be seen to be a nearly-meaningless manner. Structural steel can corrode in a manner of days if left exposed, but when protected by paint and masonry the process takes decades. The fact that curtain walls were in general known to not leak – in other words, wind-driven rain was not found to be penetrating to the inside face of the exterior walls – should have been evidence that the masonry of the walls was providing some protection to the steel.

The 1900 Broadway Chambers Building was, like the St. Paul, a major structure. The 18-story, 72m skyscraper was designed by Cass Gilbert with Purdy & Henderson as the structural engineers. The building had the typical construction of steel frame supporting terra-cotta tile-arch floors and a brick and terra cotta curtain wall. Unlike Post's designs, which tended to use masonry detailing to support projecting decorative elements, Purdy & Henderson supplied a more modern system of multiple spandrel beams to support the flat wall areas combined with out-set secondary steel members supported on brackets to carry projecting water-tables and cornices. An article describing the building made a point of the "high degree of engineering skill" required for their design and construction, and explicitly discussed the difference in longevity between steel bridges and buildings where the engineer's "experience does not necessarily give him the knowledge needful to preserve a structure that cannot be got at for periodic painting." The description of the building made the same points as the other discussion regarding accessibility and the need to protect steel against contact with water and air; it differed from Freitag in recommending the use of cement coatings:

> This is a question involving the life of these buildings. It is well known that iron or steel unless protected is liable to rust and ultimate destruction. To meet this in bridge construction repeated painting can be done. But the case is different with these structures. After the building is erected its steel frame work is not accessible, and the problem is to conserve the coating of paint put on when the structure is first put together. This coating, no matter how good, will not endure when exposed. It must therefore be perfectly protected. Corrosion cannot proceed without both moisture and air, and with good painting and good covering there is

no reason why steel framing should not be protected from both. Without a coating of paint iron or steel could be protected perfectly by the use of Portland cement, which is a perfect conservator of iron. In a building the steel framework must be protected form both corrosion and fire. The cement, while a protection against corrosion, will not answer for fire, but special means must be used. For this purpose porous terra cotta of good thickness affords the best protection. (n.a. 1900)

FACADE INSPECTION AND STEEL DETERIORATION

The discussion of longevity gradually faded. The commercial success and growing popularity of steel-frame construction, most publicly seen in the skyscraper height competition of the 1920s, which culminated in the 1930, 319m Chrysler and 1931, 381m Empire State Buildings, gained for this form of building the success that made it seem normal. The Pabst study may have also helped ease the concerns of architects and engineers, and the kind of failure that William Sooy Smith thought possible after a few years did not occur.

A series of incidents in the 1970s showed that steel framing was deteriorating in high-rise buildings to an extent that threatened the safety of passers-by. In New York, the best-known event was the 1979 death of a Columbia University student from injuries sustained when she was hit by a falling piece of a decorative stone lintel from an apartment house owned by the university. (Gupte 1979) The following year, Local Law 10 was enacted, requiring more than 10 000 buildings in the city to have their facades inspected by professionals on a five-year cycle. This law was amended and expanded in 1998 to include all exterior walls on tall buildings regardless of accessibility or proximity to public streets, and similar laws have been enacted in Chicago, Boston, and other cities. (May 2004, p. 31)

Engineers and architects performing examinations under these laws have found that steel deterioration is common to all of the steel embedded with exterior walls: beams, columns, connections, and the secondary members used to support ornamental masonry. Figure 3 shows two spandrel beams and a column, all with severely pitted surfaces and material loss from corrosion. Horizontal surfaces, such as the flanges of beams or the tops of bracketed connections, appear to be the most vulnerable as water traveling within the masonry can sit on these surfaces for long period of times. Paint has been found to inevitably fail: beams are often found to have paint intact in areas from which water drains and paint missing in areas where water pools. Figure 4 shows a spandrel beam with intact paint on the upper portion of its web despite corrosion on the lower web and bottom flange.

Figure 3: Author's photograph of a corner column at 720 Park Avenue, New York. The white is temporary protection where masonry has been removed; the removal shows two channel spandrel beams and a wide-flange column.

Figure 4: Author's photograph of a wall probe at 720 Park Avenue. The main spandrel beam (A) has intact paint on the upper portion of its web and rusting on the lower web and bottom flange, despite being set back from the wall face (C). The secondary beam (B) that stabilizes the cornice (D) is heavily rusted.

Steel corrosion threatens public safety and buildings' long-term stability in two ways: first, by weakening the structural frame to the point where collapse is possible, and second by cracking and displacing curtain-wall masonry through the mechanism of rust-jacking. (n.a. 1978) The second danger is far more prevalent than the first, and is actually considered helpful during investigations. Initial investigation take place with the curtain walls intact and masonry is removed only when there is a reason to suspect steel damage at a specific location. The effects of rust-jacking often provide that reason, and probes are cut where cracks and displacement are noted. Figure 5 shows the crack adjacent to the masonry-removal probe shown in Figure 4.

Figure 5: Author's photograph of a wall probe at 720 Park Avenue, immediately adjacent to Figure 4. The web of the secondary beam is rusted completely through (F) suggesting further removals are required. The probe was located based on the crack (E) in the visible face of the wall (C).

During nearly thirty years of organized facade inspection in New York, corroded steel has led to every outcome from full steel repair and historically-accurate recreation of the masonry removed for access (many buildings, including 720 Park Avenue, shown in Figures 3, 4, and 5) to complete removal of the ornamental masonry (as at the now-demolished Mayflower Hotel). When steel repairs are required, designers must answer the question of how to protect the steel against future corrosion. One of the popular solutions is to paint the steel and then coat it with Bithuthane, a brand-name asphalt-impregnated cloth that is essentially similar to the "asphalted felt" that George Post used on the St. Paul Building and recommended for use on all steel frames.

CONCLUSIONS

We study history for many reasons, one of which is to learn from experience. In the case of construction history, we must distinguish between studying the technology of a past era and studying the lessons of that technology's use. The technology itself is often no longer viable because of changes in buildings' use, living standards, or code requirements. For example, the use of 1890s-style solid masonry curtain walls has ended because of its cost relative to veneered cavity walls, code requirements for expansion joints, and concerns about waterproofing and thermal insulation. However, the lesson of this technology, that inherent flaws known at the time of construction may take decades to manifest themselves, is one that is applicable to any new building technology. Had concerns over the longevity of steel structure embedded in masonry been more widespread in 1900 and led to thorough waterproofing such as that George Post used in the St. Paul Building, we might have fewer old skyscrapers because of the increase in construction cost, but it is likely that we would have far fewer repairs to perform now. More importantly, had the people who publicized the condition of the Pabst Hotel as proof that concern over the steel was unfounded recognized that their study was conducted too soon after construction to have real meaning, the initial concerns might not have faded.

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