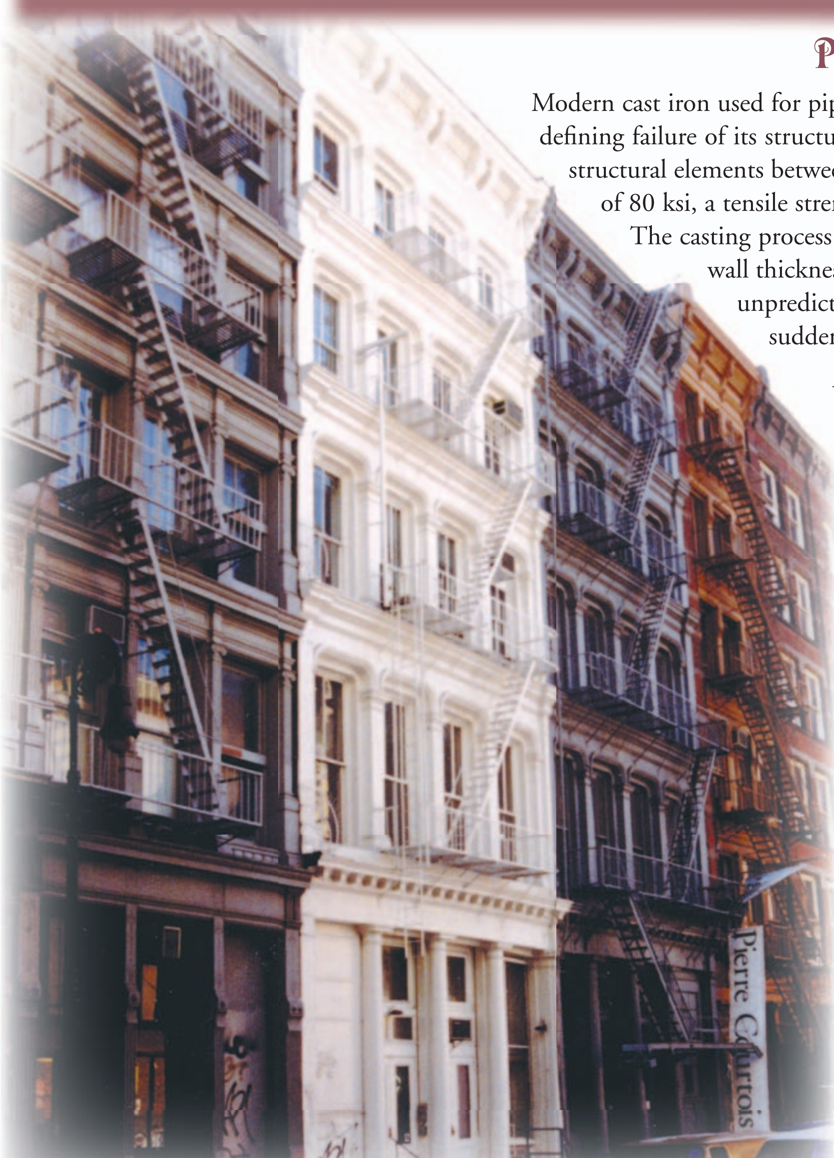
Preservation Engineering...

By Donald Friedman

Cast Iron

Cast iron is the only structural material extensively used and then abandoned. Other materials used before 1850 (wood and masonry) are still in use, while wrought iron was displaced by similar steel. The presence of cast-iron immediately marks a building as "old," regardless of recognized historic status. Because the most recent code references to cast iron were written in the early twentieth century, most engineers are unfamiliar with its properties and uses.



The four facades at center are entirely cast iron except for the wood windows frames.

Properties and Use

Modern cast iron used for pipes is called "ductile iron," specifically to distinguish it from the defining failure of its structural predecessor: unpredictable brittle failure. Cast iron used for structural elements between the late 1830s and 1910 typically had a compressive strength of 80 ksi, a tensile strength between 10 and 15 ksi, and no clearly-defined yield point. The casting process also left flaws in the iron (such as blow-holes, bubbles, varying wall thicknesses, imperfectly joined seams) that serve to concentrate stress in unpredictable ways. Engineers' and builders' awareness of the potential for sudden, catastrophic failure gradually spread after 1860.

American use of cast iron gradually spread from architectural elements like shutters and storefront window- and door-frames, to facades composed of closely-spaced iron columns and spandrel panels, to interior columns. Beams other than the flat-plate spandrels were rare, but inverted-Ts and unequal-flange Is were occasionally used until the 1870s. (Some of the earliest scientific materials tests were conducted in the 1840s on cast iron and established the tensile-to-compressive strength ratio, leading to the unequal-flange configuration.) Concerns about fire protection, particularly after the 1871 Chicago fire, led to the later development of double columns: an inner structural iron shell and a thinner outer shell, with plaster fireproofing filling the annular space between.

The rise of ductile iron framing – first wrought-iron, starting in the 1850s and peaking in the 1880s, and then steel, starting in the 1870s – marked the beginning of the end for cast iron. The lower direct-compression strengths of wrought iron and steel were less important than the safety provided by ductile behavior and high tensile capacity. Through the late 1880s and 1890s, the engineering press was full of arguments against the use of cast-iron in multiple-story buildings, even while that use continued. At that time, architects often had general contractors take responsibility for the framing, so that there was no designer input on the structural materials and systems. There were numerous collapses of cast-iron column buildings in the 1880s and 90s, typically attributed to poor foundation design, culminating in the 1904 collapse during construction of the Darlington Apartments in New York. The Darlington collapse, which killed 26 laborers, was later described as the final argument that eliminated cast-iron use in multiple-story buildings.

Renovation and Reuse

Given the inability of cast-iron structures to meet current requirements for ductility and predictability, there is no rationale that allows for increased load on existing iron elements. Alterations should be planned around substituting one load for another. For example, if a warehouse is converted to residential use, the recovered live load may be enough to justify adding a new penthouse.

It is possible to create new connections through the use of bolts in drilled holes. Burned holes should be avoided to prevent the creation of thermal stresses, as should the use of impact drills. High-strength bolts cannot be tensioned for the same reason that the original connections did not use hot-driven rivets: the local stresses will likely crack the connection flanges. Welding is not recommended because the presence of carbon inclusions in the metal interferes with creation of a weld bead, and because of the likelihood of creating thermal stresses at the base of the weld.

An interior cast iron column supporting a steel girder and wood joists.

It is important to remember that nearly all cast-iron structures have performed well (albeit in limited applications), and that the hazards presented by flaws in the iron do not suddenly appear a year after the iron was erected. Careful consideration of the effect of proposed alterations on existing cast iron can prevent changes in loading or material condition that might cause collapse.■

Floor Systems

Old floor systems confuse engineers and contractors more than any other building element. Most of us are aware that cast-iron columns and wrought-iron beams were once used, but the obsolete floors that spanned between beams are little-known except among those who have seen them. There are three basic types of floor systems in metal-frame buildings: arches, catenaries, and beams. In all three cases, the floor spans between two supports, typically iron or steel beams, and are repetitive in the horizontal direction perpendicular to the span. That repetition allows any of the types to be analyzed on a "per-foot" basis, and also means that the feasibility of cutting new openings depends on opening orientation as well as size.

Arch Floors

The 1871 Chicago fire emphasized to designers and builders the need for (relatively) lightweight and (relatively) inexpensive floors for frame construction. Widespread use of terra-cotta tile-arch floors dates from the 1870s; the system was still in use as late as World War I. The earliest tile arches were similar to the less-popular brick vaults that had been used in some iron-beam buildings as early as the 1850s, with segmental cross-sections that left the beam bottom flanges exposed. These floors cannot be considered fire-resistant unless a plaster or gypsum-board ceiling is hung below to protect the beam bottoms; the fill layer at the top is not structural but is the fireproofing for the beam tops.

There were two significant problems with the segmental vaults: the curved shape created a large depth of fill over the beams and required complex falsework during construction. Flat-arch versions of the tile floors became popular in the 1880s. They were not as strong as the segmental arches but were still stronger than the beams that supported them; more importantly, they encased the beams entirely in fireproofing material.

Other arch floors existed, notably several versions of mass-concrete arches, where a metal form (wire mesh or corrugated sheet iron) was placed between the beam bottom flanges and wet concrete was dumped in to fill up to the floor surface. These floors were heavier than tile arches and required fireproof ceilings.

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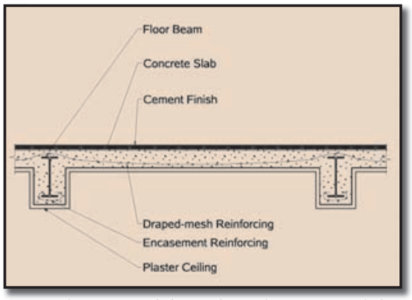
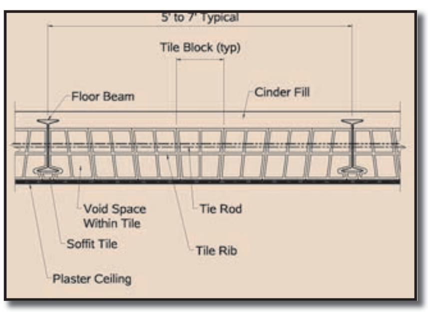
Photograph of hole cut through tile arch floor.

Catenary Floors

Draped-mesh slabs were first developed in the 1890s and were the most popular form of "fireproof" floor between 1910 and 1940, or between tile arches and concrete on deck. The wire in these floors acts as a series of catenaries: the wires ran over the top of floor beams upset into the slab and then draped down towards the bottom of the slab between the beams. The beams act as anchorages for the reinforcing-wire catenaries carrying the floor loads in tension. The concrete slab itself was unimportant structurally, although it provided a flat, stable floor and fireproofed the wires. The concrete strength was therefore theoretically unimportant, and was often made low in practice through the cost-driven use of coal cinders as coarse aggregate. An analysis of a draped-mesh slab, performed without knowledge of the system and using current assumptions, would show a slab grossly under-reinforced by modern standards for flexural concrete design. In order to work with these slabs, the old catenary formulas must be used, because their assumptions better reflect reality. The relatively greater surface area of wire, compared to rods and the porosity of the slabs, also make checking for reinforcing corrosion a priority during examination.



Typical section of draped-mesh concrete slab.



Typical section of terra-cotta tile arch floor.

Some of the early versions of catenary floors have individual wires strung across the building like piano wires instead of mesh. These floors are more vulnerable to loss of anchorage since they don't have cross-wires to aid in development.

Beam Floors

Modern floor systems – such as concrete on composite deck, formed concrete one-way slabs, and precast concrete plank – are beam systems designed for flexural shear and bending. Formed one-way slabs entered common use in the United State after 1900 in concrete buildings, with some use in high-exposure portions of steel buildings. The other two are post-World War II developments.

Early concrete slabs in steel buildings often have oddly-shaped reinforcing bar types, all intended to create extra surface area for steel/concrete friction. These bars need to be carefully checked for development in modern analysis, and may cause excessive splitting if located too near the surface.■

Structure in Historic Buildings

Labels can be confusing: my degree is in civil engineering, I consider myself to be a structural engineer, and my work is best described as preservation engineering. The last label is not widely understood. Engineering principles remain the same whether they are applied to new construction, alteration, or restoration, but translating those principles into specific design and analysis methods differs. By "preservation engineering," I mean the application of engineering techniques to historic buildings in context, applying modern analysis and design techniques to elements quite different from those currently used.

Civil engineering has long been divided into sub-fields, such as structural engineering for buildings. The field of preservation engineering is distinguished not by materials or building types, but rather by an approach. Analysis and design in new-construction projects apply current knowledge, while preservation engineering requires both questioning the assumptions buried in current design, and the reuse of old design techniques.

Structural engineers learn early that design models and formulas contain assumptions, such as concrete on the tension side of reinforcing having no strength and clip angle connections acting as simple supports. These assumptions have been optimized for the forms expected in new construction. If masonry vaults were common today, we could expect design assumptions concerning arch span-to-rise ratio, allowable percentages of differential abutment movement, and estimated rotational stiffness at arch-to-wall joints.

Analysis of old structural systems may require abandoning current models, formulas, and even codes when they do not agree with physical reality. Engineers encountering old structures must abandon preconceptions about how it is supposed to work, which is another way of saying that they must move away from code assumptions and towards first principles. Actual loading mechanisms; actual force transfer mechanisms; and locations of tension and compression within beams, arches and other compression elements, and catenaries and other tensile elements are more useful schematic analyses than code requirements. Assumptions can be tested by simply questioning the context of ordinary techniques: if analysis shows gross overload in a floor that has performed well, one should review the analysis method to ask if the floor is actually overloaded before looking for the best method of reinforcing the floor.

Many existing buildings contain archaic structure – structural elements that met the standards of their time of construction, and can be shown to meet current standards but are no longer used. Archaic design techniques can be reused although they may require explanation for clients, other members of a project team, and building officials, even in as simple a case as using the AISC Allowable Stress steel code where it is better suited to existing built structure than the Load and Resistance Factor code.

The architectural preservation and adaptive reuse movements, the green-building concept of reusing material, and redevelopment of town and city centers have all increased the need for preservation engineering. Architects, owners, and planners – the people who define most projects where engineers are employed – are increasingly saving old buildings, regardless of the formal designation as "landmarks." The challenge for engineers is to adapt our methods and keep pace.

Donald Friedman, P.E., is a structural engineer consulting on historic structures for architects, engineers, and building owners. He is the author of Historical Building Construction and the Investigation of Buildings.