Cast iron: A historical background

Material isn't used anymore, but still present in many historic buildings, so be aware of its limitations.

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Around the turn of the 20th century, the first generation of high-rise buildings were shaping skylines across America, first in Chicago and then in New York. In those days, wrought iron and medium steel were the building materials of the future. Both materials were strong in tension and compression and their malleability allowed for uniform mass production. But a third alloy was still in use: cast iron.

Introduced as a framing material in the 1830s, cast iron presented builders with an alternative to masonry bearing walls. It was relatively light weight and strong in compression, and, crucially, it allowed for the construction of taller and slimmer buildings. But cast iron was also notoriously brittle, prone to cracking, and weak in tension and shear – a deficiency that limited its use outside of column members. Furthermore, the production of cast iron often yielded unpredictable results. Irregularities in elemental composition and member dimensions were endemic to the casting process. Eventually problems like these, along with the increasingly refined and reliable production of competing alloys such as wrought iron and medium steel, relegated cast iron to purely decorative uses. Nevertheless, cast iron columns still frame many historic high-rises in the United States. For structural engineers, a background knowledge of cast iron construction is a valuable asset. In markets rich with historical structures like New York, Chicago, and Boston, sometimes it's a job requirement.

Cast iron columns come in three main structural shapes: the H-section, the cruciform section, and the hollow cylindrical section. According to the early 20th century text Structural Iron and Steel, by the mechanical engineer W.N. Twelvetrees, H-sections "were largely used in mills and factories, chiefly because of the convenience (they) offer for the attachment of brackets for shafting." Cruciform sections were "considerably used, (but) ... expensive." The hollow cylindrical section was more common in commercial buildings and was "judged by the criterion of strength per unit weight of metal... the best and most economical of all" the aforementioned structural shapes. Hollow cylindrical sections were made with flat and fixed ends and rounded or jointed ends. These ends, whether flat or rounded, were then fitted into base plates for lateral stability.

To get a feel for the structural design and analysis of cast iron, the New York Building Codes of 1897 and 1901 are great resources. The 1897 NYBC establishes the Gordon Formula (to be used with a safety factor of five) as the standard means of valid cast iron column design. The Gordon Formula was developed by the academic Lewis Gordon and built on the experimental research of Eaton Hodgkinson, as well as the work of the mathematician Leonhard Euler. Euler explored the column from an ideal mathematical standpoint, while Hodgkison took his work in a different, more practical, direction. Hodgkinson's conducted experiments on column strength in 1840, publishing his results where he could throughout the decade. Structural Iron and Steel briefly describes his conclusions: "Short columns, in which the height is not greater than four times the diameter, are fractured by actual crushing of the material... Medium columns, whose length is less than 30 and more than 5 diameters, are distinctly affected by bending stress, but the weight required to cause fracture in this manner is so great that crushing force becomes manifest, and the column yields to the joint action of the two forces. Long columns, whose length is more than 30 diameters, fail by flexure... the direct breaking weight is far below the crushing strength of the material."

Hodgkinson's work was voluminous, but his conclusions were much less elegant than Gordon's. The Structural Designer's Handbook, written by early ASTM member William Fry Scott in 1904, remarks that while "Gordon's formulae (were) deduced from Hodgkinson's experiments, they (were) more generally used than Hodgkinson's own." The formula distinguishes between columns with both ends flat and fixed and columns with rounded or jointed ends. For the latter:

$$P = \frac{fS}{1 + a\left(\frac{l}{r}\right)^2}$$

Where 'P'=breaking load of the column in tons, 'S'=sectional area of the column in square inches, 'l'=length of the column in inches, 'd"=least diameter of the column in inches, 'f'=strength of the material in tons per square inch, 'a'=a constant depending upon the sectional form of the column.

For the former:

$$P = \frac{fS}{1 + 4a\left(\frac{l}{r}\right)^2}$$

Advances in materials science were happening rapidly, though, and by 1901 the NYBC preferred a straight-line formula (which had the advantage of embodying its own safety factor) over Gordon's.

$$u_s = f - m \cdot \left(\frac{l}{r}\right)$$

Where 'u_s'=working stress, 'f'=maximum allowable compressive strength of the material, and 'm' is a constant. According to the 1901 NYBC, for cast iron columns 'f'=11,300psi and 'm'=30.

Both formulae are empirical equations, and as such are limited in their respective abilities to provide accurate results at high slenderness ratios. Because of this, both the 1897 and 1901 NYBC set explicit upper limits on slenderness ratios. Despite these limitations, the Gordon and straight-line formulae can still help contemporary structural engineers determine the intent and considerations involved in the design of these columns – invaluable information for any structural analysis.

Materials science has largely left cast iron behind, but there is some contemporary research dealing with the old alloy. In 2003, Professors Jacques Rondal and Kim J.R. Rasmussen concluded that the yield stress of cast iron equals approximately half its ultimate compressive strength – a judgment that matches AISC standards for medium A9 steel during the early 20th century.

Engineers and researchers of every generation are eventually confronted with cast iron's fatal flaw: its inconsistent composition. The possible imperfections of cast iron columns are manifold: wall thickness variations, blow-holes, contaminants, internal stresses from uneven cooling, and more. Cast iron columns were often designed with safety factors over eight times what we see today. In Structural Iron and Steel, the author points out that: "Very little useful information is to be derived from external contemplation (of cast iron columns), and if the architect or engineer wishes to be quite sure that the metal is uniformly of specified thickness, he must cause holes to be drilled at different points, so that actual measurements may be taken."

Proceeding from the formulae discussed above (with slight modification), the structural analysis of cast iron can be divided into five steps:

1. Verify existing column construction – drawings over a century old are seldom accurate and unchanged. Coupon tests may be required to verify metal composition.
2. Obtain the full unbraced length, L. Divide by the least radius of gyration of the member to find the slenderness ratio.
3. Calculate the loads on the columns.
4. Use the tables or formulas from the applicable building code according to the construction time period (New York Building Codes – 1897, 1901, 1916, etc...) to obtain the allowable "working stress."
5. Compare the actual stress with the working stress.

A structural engineer with a working knowledge of cast iron will, most importantly, be aware of the material's limitations. Ultimately, properly designing around existing cast iron columns is a matter of engineering judgment. This is, of course, an uncommonly qualitative assertion in our very quantitative era. Then again, cast iron doesn't belong to this era, but to another.

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