Practice Points NUMBER 02

The Metropolitan Floor: Modern Analysis of an Archaic Structure

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Introduction

One of the common difficulties in the restoration and reuse of historic buildings is determining whether obsolete or archaic structural elements meet current standards. These requirements include the basic ideas that the structures must be safe and serviceable, as well as the specific code requirements that enforce those ideas. Addressing the code issues may mean showing calculations or similar hard evidence to building officials unfamiliar with past practice to demonstrate that historic elements meet today's regulations.

In the case of the Metropolitan Floor system, the combination of a now-uncommon structural system (a catenary floor) with a now-nonstructural material (gypsum) raises questions of load capacity, fire resistance, and reuse ability. The method of analysis described here addresses these issues.

Fig. 1.
Exterior of a building erected in Baltimore in 1927 as a private club. The Metropolitan Floor is still in place, and the building is currently undergoing renovation. All images by the author.

Historical Context and Floor Description

The technology of structural-steel framing reached maturity in the United States between 1890 and 1910, long before reinforced-concrete technology was available at a similar level. The use of bar-reinforced, formed-concrete slabs in steel-framed buildings is rare before 1910, and buildings with this system constitute less than half of the existing buildings constructed between 1910 and 1960. Modern concrete-on-metal-deck floors were not developed until the 1950s, so many buildings constructed before 1960 have archaic floor systems, not the familiar reinforced-concrete or concrete-on-deck.

The need for inexpensive, fire-rated, and structurally reliable floors became acute in New York City and Chicago during the 1890s as many large steel-frame buildings were constructed for commercial and residential use. The standard floors prior to 1900 were terra-cotta tile arches, which were thick (often 16 inches of terra cotta and fill) and heavy. Alternate floor systems that would reduce the weight and thickness of the floor without increasing construction expense or sacrificing fire protection were needed. The development of alternate systems was conducted by parties interested in proving the value of a system, including individual engineers, companies with proprietary systems for sale, and insurance companies.[1] Beginning in 1896, the New York City Building Department (NYCBD) and Columbia University began a program of testing alternate flooring systems following the requirements of the New York City Building Code. Many of these floors were being used nationwide as late as the 1930s. When large-scale commercial construction activity resumed after the Depression and World War II, the Metropolitan System, like most of the proprietary systems, was no longer used.

One of the floor systems approved by testing by 1899 and used sporadically from the 1900s to the 1930s was the Metropolitan Floor, patented circa 1895 (Fig. 1). It was also later sold under the name "Pyrofill." The system consists of a series of steel wires that are draped over the top of the floor beams and serve as catenary supports for the floor loads (Fig. 2). The wires, arranged in twisted pairs, are encased in a slab composed of gypsum with small wood chips embedded

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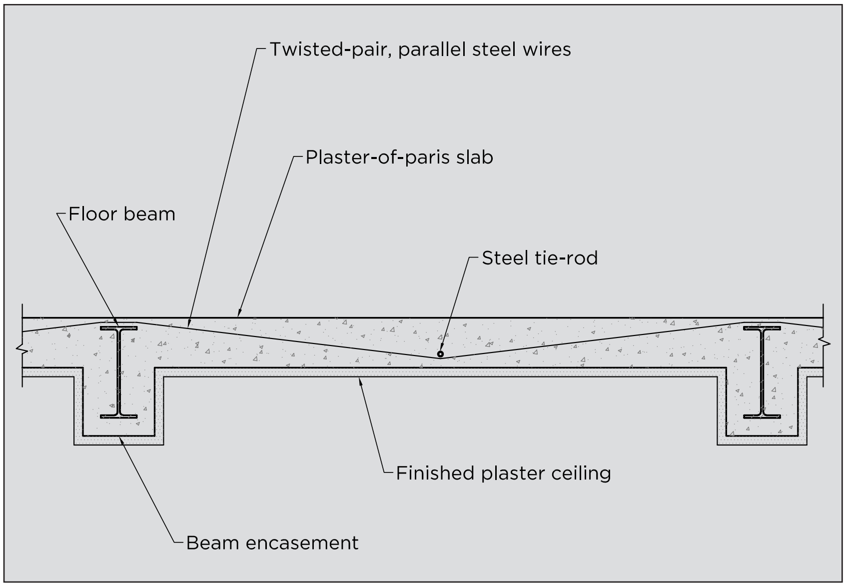

Fig. 2. *Section through Metropolitan Floor parallel to span showing the basic construction technique.*

in it (Figs. 3 and 4). The slab serves the structural function of providing a flat and fire-resistant surface. It spans the 1 to 3 inches between the wires but does not participate as a major stressed element. The wires are anchored at all intersecting slab edges by simple twisted connections over light steel supports (angles or straps) bolted to the structural frame (Fig. 5).

Analysis Methods

The continued use of the Metropolitan Floor is not prohibited by code but is outside of ordinary code requirements and restrictions. For example, there is no contemporary commonly used method of load analysis for the floors, nor is there contemporary fire-performance data. However, the International Building Code allows for the use of out-of-the-ordinary, rational methods of structural analysis (for example, in section 1604.4, “Any system or method of construction to be used shall be based on a rational analysis in accordance with well-established principles of mechanics”), and it can be demonstrated that the Metropolitan Floor passed tests equivalent to the modern requirements. The analyses that follow use historic data but meet current code requirements.

Load Capacity of the Metropolitan Floor

Because the only requirement for use of the Metropolitan Floor system in 1896 was that it successfully pass the NYCBD-Columbia University tests, it can now be said to have been originally designed empirically, without a specific structural analysis. The Metropolitan Floor, like other catenary floors, is a series of catenaries that support vertical loads through tension within the wires and oriented parallel to them. There are existing analyses for catenaries with fixed supports: both general formulas based on statics and simplified formulas that became part of building codes and manufacturers’ recommendations during the first half of the twentieth century.

One of the simplified catenary formulas that was publicized by the wire-products division of United States Steel was also incorporated in the New York City Building Code in the mid-twentieth century and remains in effect.[2] Since the national model codes no longer include catenary floor systems, this formula is likely to be lost from current practice when New York adopts the International Building Code. The referenced versions of this formula refer to stone or cinder-concrete slabs; however, the results closely agree with the stated capacities of the Metropolitan Floor’s gypsum slab. It should be noted that this formula restricted the allowable tension in the wire to 20 kips per square inch (ksi), despite the fact that the yield stress for “cold-drawn steel wire” as established by ASTM A82 in 1927 was far higher. The 1934 version of ASTM A82, which was in use through the mid-1950s and represents the wire technology of the 1930s, has a general minimum yield stress of 64 ksi, with a minimum yield stress for wire to be used in mesh of 70 ksi.[3] The minimum yield stress expected in historic wire systems has been conservatively established as 50 ksi.[4] Given that current floor-design codes have total safety factors in the range of 1.5 to 1.8, it is evident that there is excess capacity in the original design of the Metropolitan Floor.

The simplified formula in the New York code is

$$W = 3(C)(A_S) / L^2$$

where W is the total allowable load in pounds per square foot, L is the beam-to-beam centerline spacing (in feet), A_S is the wire cross-sectional area per foot width of slab (in square inches), and C is a constant representing the maximum allowable wire stress and equal to 20,000 pounds per square inch. For example, by this formula pairs of 12-gage wire at 1½-inch spacing and a 6-foot-4-inch beam-to-beam spacing result in a 253 psf combined dead- and live-load capacity.

A more basic formula derived straight from statics (by approximating the catenary curve as a parabola) is

$$T = [(w_{floor})(s)(L^2) / 8h] + (w_{floor})(s)(h)$$

where T is the tension in a wire (in pounds), w_{floor} is the combined dead and live load (in pounds per square foot), s is the wire spacing (in inches), and h is the wire “drape” (the vertical distance from the wire’s highest point at the beam to its lowest at midspan). By setting T equal to the allowable tension stress multiplied by the wire cross-sectional area, the maximum floor load can be determined. Using the previous example, with a 3-inch drape assumed for the 4-inch slab thickness measured, the wire shows a tension stress of 30 ksi at 253 psf loading, but setting the wire stress to a maximum of 20 ksi still allows for 167 psf total load. These capacities fall within the original code-required live loads of 75 psf for office use or 90 psf for a place of assembly and a dead load of 60 psf for a 6-inch gypsum slab.[5]

In short, these calculations demonstrate that these slabs have a structural capacity that is similar to that assigned by the 1899 New York City Building Code (and based on the 1890s NYCBD-Columbia University testing) and typically adequate for ordinary commercial and residential occupancies under current codes.

Fire Rating

Today, fire ratings for new structural assemblies are determined by the Underwriters Laboratory using tests based on the requirements of specification ASTM E119. A comparison of that specification to the NYCBD-Columbia University test that the Metropolitan Floor system is known to have passed demonstrates that the Metropolitan Floor exceeds the modern requirements for a three-hour fire rating.

The existing test data come from a series of tests performed in the late 1890s and early 1900s by various agents under the supervision of the New York City Bureau of Buildings (the predecessor agency to the current Department of Buildings), in accordance with the requirements of the New York City Building Code at that time.[6] That code provided for the use of nontraditional floor construction as follows: "Or between the said beams may be placed solid or hollow burnt-clay, stone, brick, or concrete slabs in flat and curved shapes, concrete or other fireproof composition, and any of said materials may be used in combination with wire cloth, expanded metal, wire strands, or wrought-iron or steel bars; but in any such construction and as a precedent condition to the same being used, test shall be made..."[7] The test is defined elsewhere in the code as being performed on a completed sample panel of floor; it consisted of heating the floor and maintaining an average temperature of 1700°F for four hours under 150 psf live load, followed by rapid cooling of the floor through the use of a simulated firefighter's pressurized hose stream and top-surface flooding, followed by reloading the floor to 600 psf while measuring deflection. Throughout the process, the physical integrity of the floor and its ability to stop vertical flame spread were to be measured.

When the New York code requirements for testing as implemented by Columbia University are compared to ASTM E119, it is clear that the nature of the tests is essentially similar: paragraph 4.2 of ASTM E119 states that the "test exposes a specimen to a standard fire controlled to achieve specified temperatures throughout a specified time period. When required, the fire exposure is followed by the application of a specified standard fire hose stream." The temperature curve defined in ASTM E119 paragraph 5.1 is more complex than the simple constant temperature used in the New York test, but the ASTM standard provides a formula for comparing nonstandard test results (in hours tested at specific

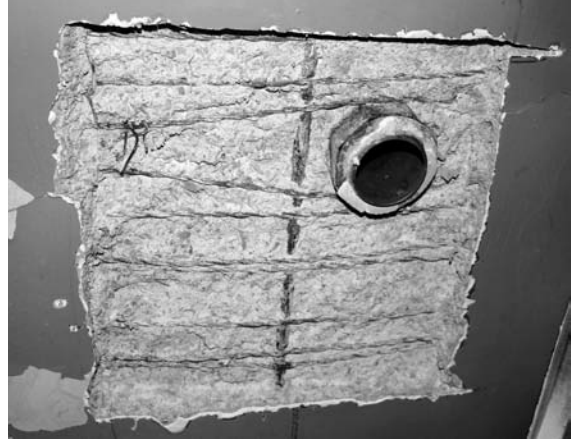

Fig. 3.
Probe through ceiling plaster exposing twisted wire pairs and midspan hold-down rod. Note the wires "pushed aside" at the embedded plumbing sleeve.

temperatures) to the standard test results in paragraph 8.4. This formula provides a correction factor

$$C = 2I(A-A_s) / 3(A_s + L)$$

where I is the fire-resistance rating in hours indicated by the non-standard test, C is a correction factor to be added to I, A is the area under the curve of average furnace temperature for the first three-fourths of the indicated period for the non-standard test, A_s is area under the standard furnace curve for the same part of the indicated period, and L is a lag correction in the same units as A and A_s (54°F·h or 30°C·h).[8] Note that the area under a time-temperature curve is a measure of the total heat applied to the floor during the test.

The requirements of the ASTM test are equivalent to or less conservative than the NYCBD-Columbia University method. For example, the 600 psf reloading requirement from the New York test no longer exists. Given that the New York tests were so similar to the current testing procedures, the comparison method in ASTM paragraph 8.4 is applicable; using the correction formula to compare the total amount of heat resisted during the two tests provides a result that the New York test of the Metropolitan Floor shows a fire rating of 3.99 hours. This result can be rounded to a 4-hour rating or more conservatively taken as 3.5 hours. Since floor assemblies are rarely required to have fire ratings greater than 2 hours, the difference is not significant.

There is a second source confirming that significant fire rating can be obtained by gypsum floor structures. The U.S. National Institute of Building Sciences has compiled data on fire ratings of the construction materials and assemblies used in historic buildings for the federal Department of Housing and Urban Development (HUD). Gypsum floors as thin as 2 inches are listed with fire ratings varying from 1.5 to 4 hours, in the same range as the Metropolitan Floor.[9]

Floor beams in the standard Metropolitan Floor are fireproofed by means of gypsum encasement integral with the slab. The HUD data shows that this detail, if undamaged, provides an acceptable fire rating. If the encasement has been partially removed, it must be replaced with new fireproofing. If the encasement has been completely removed, the structural integrity of the floor may be compromised, since the encasement provides secondary shear support where the slab meets the beam.

Reuse and Alteration

If undamaged and left undisturbed, existing Metropolitan Floor installations should be accepted as adequate

Fig. 4.
Core through floor showing the thin layer of finish plaster on bottom and the cut ends of wires.

Fig. 5.
Probe at the inside face of a spandrel beam showing wrapped attachment of the wires to secondary steel.

pending examination by a structural engineer. Since the strength of the system lies in the wire reinforcing, local damage to the gypsum slab is usually not serious and can be repaired with concrete-patching products. Water damage to the gypsum does not affect structural capacity but may require repair to provide a solid and flat top surface; however, water damage to the reinforcing wire must be investigated and repaired, since it can destroy the structural capacity.

The catenary system does not provide for the easy removal of a partial span between two beams, and the gypsum slab is too weak in tension and shear to provide good attachment for new structure. Therefore, new openings should be created between existing beams and new floor structure used as infill to create smaller openings as required. In order to maintain the integrity of adjacent slab spans, the wires must be anchored to the beams before they are cut, preferably by welding them to the top flange of the beam after the beam is exposed through careful removal of the gypsum top surface.

The gypsum slabs cannot support any direct hung load. Existing hangers fastened to the reinforcing wires or floor beams may be reused, as they will transmit load directly to the wires; otherwise, all new hung load should be fastened to the floor beams. Standard expansion or epoxy anchors set in the gypsum have little or no definable capacity, as the gypsum shear strength is both low and unpredictable.

Conclusion

The Metropolitan Floor system, while unfamiliar to modern practice, represents the use of engineering principles that have not changed since the system was first used in the 1890s. This system was originally designed empirically under an extreme live load, a form of test still used today in full-scale structural-load tests. The structural load capacity can be shown by calculation to be acceptable for new uses with live loads similar to those used in the original design, while the fire rating can be shown through code-requirement analysis to be comparable to that provided by present-day tests. This floor system is not common, but it has been observed by the author during renovations of office and other commercial buildings in New York, Baltimore, and Richmond and, with proper treatment, should be able to sustain continued use far into the future.

Notes

1. See, for example, George Hill, "Tests of Fire-Proof Flooring Material," *Transactions of the American Society of Civil Engineers* 34 (Dec. 1895): 542-568.

2. United States Steel Corporation, American Steel and Wire Division, *American Welded Wire Fabric for Concrete Reinforcement* (Pittsburgh: United States Steel Corporation, 1944). *Building Code of the City of New York*, §27-610 (2004).

3. Concrete Reinforcing Steel Institute, "Standard Specification for Cold-Drawn Steel Wire for Concrete Reinforcement, A.S.T.M. Designation: A82-34," in *CRSI Design Handbook* (Chicago: Concrete Reinforcing Steel Institute, 1952), 387-388.

4. Concrete Reinforcing Steel Institute, *Evaluation of Reinforcing Steel Systems in Old Reinforced Concrete Structures* (Chicago: Concrete Reinforcing Steel Institute, 1981), 4.

5. *Building Code of the City of New York*, p. 109, section 130 (1899).

6. Bureau of Buildings of the City of New York, *Report of the Bureau of Buildings of the City of New York for the Borough of Manhattan for the Quarter and Year Ending December 31, 1904* (New York: Martin B. Brown Co., 1905), 9.

7. *Building Code of the City of New York*, p. 80, section 106 (1899).

8. ASTM, "Standard Test Methods for Fire Tests of Building Construction and Materials," ASTM E119–00a, section 8.4.

9. National Institute of Building Sciences, *Guideline on Fire Ratings of Archaic Materials and Assemblies* (Washington, D.C.: U.S. Dept. of Housing and Urban Development, Office of Policy Development and Research, 2000), A-112.

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