Empiricist and Rationalist Approaches to the Design of Concrete Structures

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Fig. 1. Notre-Dame du Raincy, France, built 1922–1923, nave looking northwest (liturgical east). The transverse barrel vaults over the aisles were designed before the development of a rational method for their design. Photograph 2011 by Wikimedia Commons Creator: Binche.†

Design based on experience is found to be a valid design procedure, based on both engineering and epistemological considerations.

The design of buildings in general, and building structures in particular, has changed over the previous two centuries, proceeding from experience-based design, often referred to as "empirical," to a form of design in which considerations of mathematics and physics are used to predict behavior, a method often described as "rational." In the following paper, we discuss and critically assess these two approaches to the design of concrete and reinforced-concrete structures, primarily in the late nineteenth and early twentieth centuries.

If an empiricist is defined as someone who relies strictly on experience without attention to theory or logical proof and if a rationalist is defined as someone who relies exclusively on idealized mathematical models and logical proofs without appeal to experience, then no engineer is one or the other. Empiricist appeals to experience are most successful when presented in the form of a logical argument, and rationalists could not have come up with idealized models without recourse to experience of the world being modeled. However, a trend at the nexus of engineering pedagogy, engineering design, and engineering for historic preservation neglects this more complicated view of empiricist and rationalist approaches. In the spirit of what is sometimes referred to as "scientific rationalism," contemporary engineers often dismiss knowledge based on experience and prefer to credit the application of reason, in the form of mathematical models for solutions to engineering problems.[1] This approach downplays the historical reliance on empiricist approaches and obscures the practical necessity of attending to empiricist details in otherwise rationalist methods.

Historically, a reliance on empirical details can be seen in the evolution of reinforced-concrete design. Early experimenters in concrete, such as Francois Coignet and Joseph Monier, designed structures that properly supported the required loads, and they did this by relying on empiricist approaches to design.[2] Later builders, such as Francois Hennebique and Gustav Adolf Wayss, attempted to create rationalist models of the behavior of reinforced concrete and to design according to these models.[3] However, their models dealt only with limited aspects of the analysis of a reinforced-concrete beam or column, leaving the remainder of the solution to empiricist appeals. Even today, it is possible to look through modern reinforced-concrete codes and find reflections of an empiricist outlook.[4]

In this paper we identify where empiricist design occurs in concrete structures and, subsequently, argue that empiricist methods are not only effective; sometimes they may also be more effective than rationalist approaches, and in any case, they turn out to be unavoidable. Examples of reinforced-concrete design through the early twentieth century are used to illustrate the efficacy and necessity of empiricist approaches, particularly for working with new materials where a rationalist explanation has not been developed or where the rational explanation covers only limited aspects of the design (Fig. 1).

This argument involves two parts. In the first part, we discuss differing convictions about the acquisition and justification of knowledge, as they are described in the branch of philosophy known as epistemology. Having a familiarity with the philosophical details provides a helpful context for understanding the debates as they play out in engineering. From this discussion it is clear that, at the very least, empirical knowledge is on equal footing with rational knowledge, a point that supports the explanation of and justification for a more explicit recognition of the importance of empirical knowledge to engineering design. In the second part, historical cases are emphasized in order to highlight the weaknesses of design approaches that appeal exclusively to rationalist models, to document the ubiquitous role of empiricist elements in design, and show that the ubiquity of empiricist elements is inevitable, as these elements are often needed to correct the idealizations required by rationalist-design methods. Especially in reinforced-concrete design, empiricist methods are present, as evidenced by the persistent use of empirical rules in place of idealized laws. Moreover, empiricist appeals are often required, even if only implicitly, to offer appropriate corrections to the assumptions underlying rationalist-based models when these models are applied to particular cases.

Empiricism and Rationalism: Some Philosophical Background

Empiricism and rationalism represent two opposing views in epistemology, the study of how knowledge is acquired and justified. Within the western philosophical canon, the debate between empiricists and rationalists can be found as early as the ancient Greeks. Plato was a prototypical rationalist whose commitment to ideal models so conflicted with his everyday experience of the empirical world that he was led to posit the existence of an extra-empirical realm of ideal Forms. In contrast, his student Aristotle often backed away from his teacher's commitment to the reality of a completely ideal, rational other-world; instead, he spent a considerable amount of time studying the mundane empirical details of this world. He was nevertheless able to generate workable laws of nature that were not refuted until many centuries later, on the basis of new empirical knowledge ushered in by the scientific revolution.

A key figure in the scientific revolution was the philosopher René Descartes, who came, near the end of his life, to embody the rationalist approach. Descartes played an important role in the history of mathematics: he was the first, for example, to express geometrical points in terms of x, y coordinates on a graph, still referred to as "Cartesian" coordinates. Descartes came to believe that experience with the world was primarily a source of error. He preferred the certainty he could get from mathematical proofs. In his *Discourse on Method,* he claimed to have successfully doubted all the knowledge he had once derived from sensory experience.[5] He then attempted to build up a new and more certain foundation of knowledge based purely on a rationalist application of reason and logic.

The empiricist reliance on experience for the acquisition and justification of knowledge was embodied by a famous critic of Descartes, David Hume. Hume recognized the appeal of the rationalist approach. He agreed that deductively logical formulations, such as those found in arithmetic, needed no empirical justification. Given a proof that the sum of 2 + 2 is 4, he argued, there is no sense to be made of subjecting the result to empirical tests on subsequent days under different conditions. However, while Hume appreciated mathematical certainty, he did not think that kind of certainty could be applied to the real world. Subjecting mathematical proofs to empirical tests was unnecessary, not because the proofs revealed immutable truths about the world, but rather because they did not really describe the world at all. Unlike the rationalist Plato, Hume did not go on to posit a more real world where such immutable truths obtained. Just like Aristotle, Hume had more mundane concerns. He shared with Descartes the view that experiences with the real world could produce errors in thinking. But unlike Descartes, Hume thought those flaws were to some extent inevitable, because the world is a contingent, messy place. Hume argued that while there will never be absolute certainty about the world, experience can still be used to solve problems. When solutions fail, the failures can usually be explained, even if after the fact.

The difference between rationalism and empiricism can be further illustrated by investigating impacts between billiard balls, a favorite example of David Hume's.[6] A rationalist might argue that the path of the balls can be determined by appeal to the ideal laws of physics, such as the conservation of momentum and conservation of energy. The empiricist, by contrast, would be less concerned with modeling ideal pathways of potential billiard balls and more concerned with actually playing billiards.

The empiricist would likely assert that the ideal laws on which the rationalist relies could be formulated only after some experience; e.g., after observations of actual impacts. The empiricist might further object, as shown in Figure 2, that the prediction of the actual paths of any given billiard ball requires attention to details not accounted for in physical laws, e.g., friction; experience with this particular billiard table, which is known to be warped; or spin (described in Figure 2 as "english").

In current engineering practice and pedagogy, as well as in the treatment of historical design, rationalist approaches are often emphasized in ways that downplay the importance of empiricist methods. With respect to structural design in particular, the epistemological debates between empiricism and rationalism are especially salient. The rationalist method of engineering often makes references to a "scientific" viewpoint (where "science" stands in for more theoretical sciences that are highly mathematized and focused on modeling in idealized conditions). For example, idealized models are used to explain how a reinforced-concrete structure behaves, as applied to an understanding of how to make the structure adequate to resist a given set of loads, as in laws of equilibrium, laws of flexure, or others. Engineers working from a more empiricist standpoint often make use of methods from the more applied sciences where the idealized conditions of explanatory models are checked against conditions in the real world. Experience is used in testing materials or in applying them to a structure to determine size and reinforcement for the structure and especially in applying the lessons from previous cases that did not perform as desired.

Attending to the epistemological backdrop helps show that, when it comes to understanding building structures, practitioners who attend more explicitly to the empirical details are as effective as practitioners who focus instead on rationalist elements, such as modeling. When it comes to understanding the nature of materials and predicting their endurance and strength when assembled into structures, experience informs us as much or more than our reliance on rationalist methods. As discussed in more detail below, historical studies make particularly clear that commitments to empiricist approaches were commonplace and that structures designed according to empiricist principles performed as well as contemporary structures designed according to rationalist principles. An investigation of historic and contemporary practice also shows that the rationalist elements are not themselves sufficient: additional empiricist details are often needed for successful design, even if attention to these details remains implicit.

Empiricist Engineering Principles: Historical Cases

The empiricist design of structures by appeal to experience, reflected in simple rules and without the attempt to develop or rely on theoretical underpinnings, is prevalent throughout all periods in engineering history. Roman and medieval structures, for instance, were designed by applying numerical or geometrical ratios gleaned from experience over time, without reference to theories of mechanics.[7] Nineteenth-century wood structures were usually built from pattern books or from experience-based rules, rather than from appeals to theoretical notions of the statics of beams or their response to bending. In the nineteenth century stone structures were generally designed based

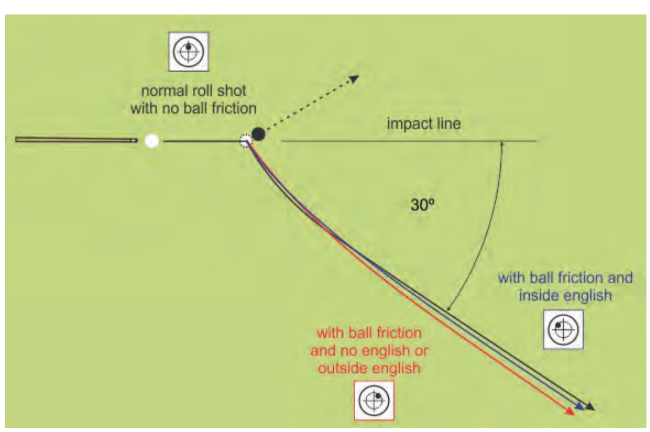

Fig. 2. An illustration of the path of billiard balls, which is determined by impact, friction, english, and other factors. http://billiards.colostate.edu/index.html, accessed Nov. 16, 2016. Courtesy of Dave Alciatore.

not on idealized laws but on empirical rules or generalizations, such as William Rankine's rule or John Trautwine's rule for the thickness of arches.

The primacy of empiricist methods is exemplified in the work of Auguste Perret, including the church of Notre-Dame du Raincy, near Paris (Fig. 1). Although a number of critics refer to Perret's use of rational ideas, and his work is justly referred to as a product of French rationalism, at least the thin-shell barrel vaults over the aisles of this church were designed empirically.[8] It was not until Franz Dischinger's publication in 1928 that engineering formulas for thin-shell concrete were available—by which time the roof of the church at Le Raincy had already been built (the construction spanned 1922–1923).[9] To all appearances the church is a product of empiricist design of reinforced-concrete structures, as are Coignet's reinforced-concrete terraces, described below. Importantly, this church endures, its vaults continuing to support the roof.

It is important for engineers to acknowledge the role of experience, because no one description of how reinforced-concrete works will cover all cases and because the available descriptions have both empiricist and rationalist components. However, engineers rarely consider the empirical elements involved in assessing the truth or justification of the assumptions that they are working with. When a historian compares analysis and design methods from one century to the next, this empiricist exercise is important.

Consider that when using a rationalist approach to constructing mathematical models of a reinforced-concrete beam in bending, a number of assumptions are made, although the question of their truth is not explicitly discussed. For example, in order to appeal to the Bernoulli-Euler model of beam bending for reinforced concrete, it is assumed that:

- there is an unstrained "neutral" axis in the beam;
- the concrete below this neutral axis is cracked;
- cracked concrete can carry no tension;
- the strain distribution is linear; and
- the strain in the reinforcement only varies with the bending moment on the beam.

The discussion in example two below shows that none of these assumptions is empirically true. Still, these assumptions have utility in the construction of a predictive model of the strains, forces, and strength of a reinforced-concrete beam. However, insofar as this idealized, rationalist model is intended to predict the actual behavior of a particular beam without further testing and further appeals to the specific circumstances, then it is patently ineffective. But appeals to empirical conditions, such as acceptance of the assumptions of flexural analysis of reinforced-concrete beams on the grounds of their utility, are seldom remarked, as engineering design is now considered to be primarily a rationalist activity.

The complex relationship between idealized models and empirical details is the topic of philosopher Nancy Cartwright's 1983 book *How the Laws of Physics Lie*. She reminds readers of what is known but seldom made explicit, namely that,

> "If the fundamental laws [of physics] are true, they should give a correct account of what happens when they are applied in specific circumstances. But they do not. If we follow out their consequences, we generally find that the fundamental laws go wrong; they are [then] put right by the judicious corrections of the applied physicist or the research engineer."[10]

Many of the assumptions underlying the mathematical models for designing reinforced-concrete structures require the sorts of adjustments Cartwright describes. Engineers are required to calibrate these adjustments relative to the empirical details of relevance to a particular case. Historically, the need to make empirical adjustments when applying the underlying assumptions of rationalist methods often led designers to avoid rationalist approaches altogether. The following two brief examples from the history of reinforced-concrete structures illustrate the weaknesses of rationalist models, the ubiquity of empiricist methods, and the necessity of appealing to empiricist methods to correct or adjust predictions of rationalist models.

Example one: concrete arches

There is a considerable late nineteenth-century body of literature outlining rationalist-design methods for the arch. The work of Rankine and Malverd Howe stand as exemplars.[11] Rankine develops elasticity equations that are applicable primarily to iron arches and incidentally applicable to masonry, including plain concrete. The Howe book was written to be applicable only to masonry arches. However, some of the particularly troublesome features of the design of masonry or concrete arches—cracking, variation in bending stiffness along the length of the arch, the middle-third rule, etc.—are not invoked in either of these methods of arch design.

All of these works make use of rationalist methods such as the equations of elasticity for an arch in bending and the construction of mathematical solutions of this problem for various idealized loading states and support conditions. However, depending on the method employed, the number of loading and support conditions is very limited, as is the case for Rankine's application. Howe's procedure is approximate, in that an incremental solution of the arch equations is used that has to be applied by constructing a large number of calculation tables. Although this approximate analysis can cover any conditions of loading or support of the arch, this method was similarly limited as it required long calculations. The length of the calculations rules out the use of this method in general, especially where simpler graphical procedures are available and especially where the proportions of the arch can be found empirically.

Empiricist methods of arch analysis were ubiquitous and were often preferred over rationalist methods. Rankine, Trautwine, and a number of French engineers published simple empirical rules for the determination of the thickness of the arch ring at the crown.[12] Rankine's method requires only the inner radius of the arch in order to make this determination, while Trautwine's method requires as inputs the inner radius and span of the

Table 1. Arch Proportions Following Rankine and Trautwine's Empirical Formulas

SPAN FEET	RISE FEET	RADIUS FEET	THICKNESS (feet) RANKINE	THICKNESS (feet) TRAUTWINE
10	2.50	6.25	0.88	1.04
10	5.00	5.00	0.78	0.99
20	2.50	21.20	1.61	1.59
20	5.00	12.50	1.24	1.39
20	10.00	10.00	1.11	1.32

arch. Here is Rankine's formula for the thickness of the arch (all dimensions in feet):

thickness of keystone = 0.35√radius (for a single arch)

And Trautwine's formula:
thickness of keystone = 0.2 + 0.25√(radius + ½ span)

Table 1 describes the thickness of the keystone calculated by Rankine's and Trautwine's method for arches of various proportions.

The remainder of the dimensions of the arch could then be worked out graphically. One example of such a construction is given by Edward Gould (Fig. 3).[13] The thickness of the arch at the joint of rupture is such that the projection of the joint on a vertical plane has the same height as the thickness at the crown. Nearly every concrete arch built in the U.S. before 1920 was designed by appeal to empiricist methods, validating their effectiveness. Figure 4, for instance, shows a construction drawing from the Freeman's Crossing Bridge, a concrete arch with a 122-foot span over the Yuba River in California, constructed in 1921–1922.[14] The radius of the intrados is 96 feet. The crown thickness calculated by Rankine's method is 3.43 feet and by Trautwine's method 3.33 feet; the as-built thickness is 3.33 feet.

These empirical rules can be further simplified by noting that they prescribe a ratio of span: arch-ring thickness, which tends to vary from 10 to 20. It is also clear that while several rationalist theories were available to late nineteenth-century designers, including Rankine, Howe, and others, most designers preferred to use empirical rules.

Example two: concrete beams and slabs

The late seventeenth-century view of Bernoulli, modified in the eighteenth century by Euler, illustrates the need for empirical adjustments to the assumptions underlying rationalist models, in this case models of bending in reinforced concrete. The Bernoulli-Euler model forms the basis for the contemporary engineering viewpoint of a beam in bending, and it is universally applied in contemporary practice to the design of reinforced-concrete beams.

In the Bernoulli-Euler model, the beam in bending has a tension side and a compression side (top and bottom, respectively, in a cantilever beam), and a neutral, unstrained axis within the beam. Because the strains are assumed to be linearly distributed, the stress is also considered to increase linearly outward from the neutral axis. However, because the concrete is assumed to be cracked and thus stress-free in tension, this stress distribution applies only to the compression side of the neutral axis. The reinforcing steel supplies the tensile force on the other side of the neutral axis, and the contribution of the concrete in tension is neglected completely. An internal lever in the beam is assumed, with the fulcrum near the face of the beam opposite the reinforcing steel and the effort applied by the force in the steel.

Since idealized assumptions produce the Bernoulli-Euler-based model of a reinforced-concrete beam, successful application of the model requires empiricist correction. As described by Frederick Turneaure and Edward Maurer, nine different stress distributions were considered before adopting, as the simplest explanation, the linear distribution of

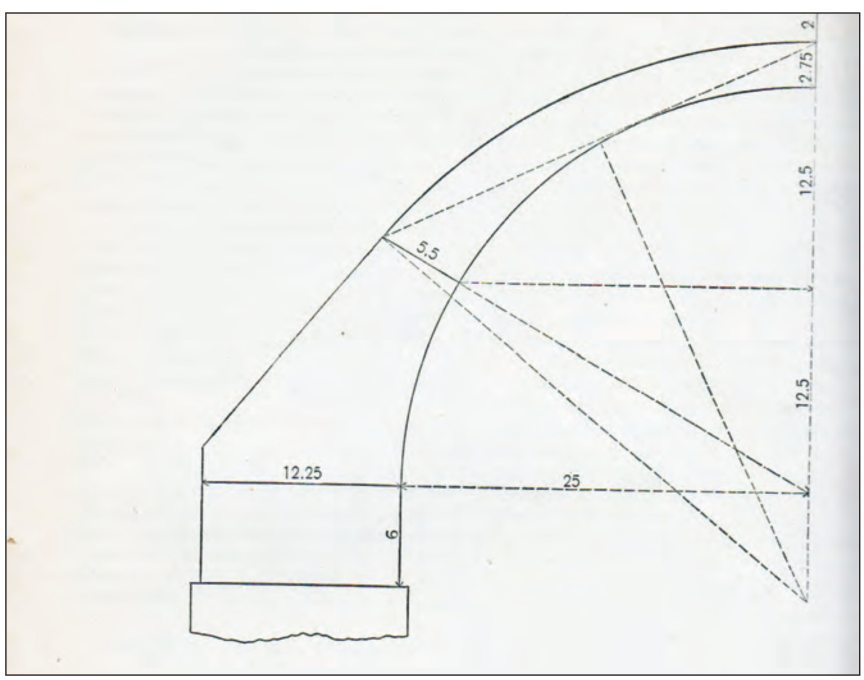

Fig. 3. Layout of a masonry-arch bridge, from E. S. Gould, "Proportions of Arches from French Practice," *Van Nostrand's Engineering Magazine* 29 (1883): 449-469. Given the thickness at the crown, the remainder of the arch is laid out on the basis of simple geometry.

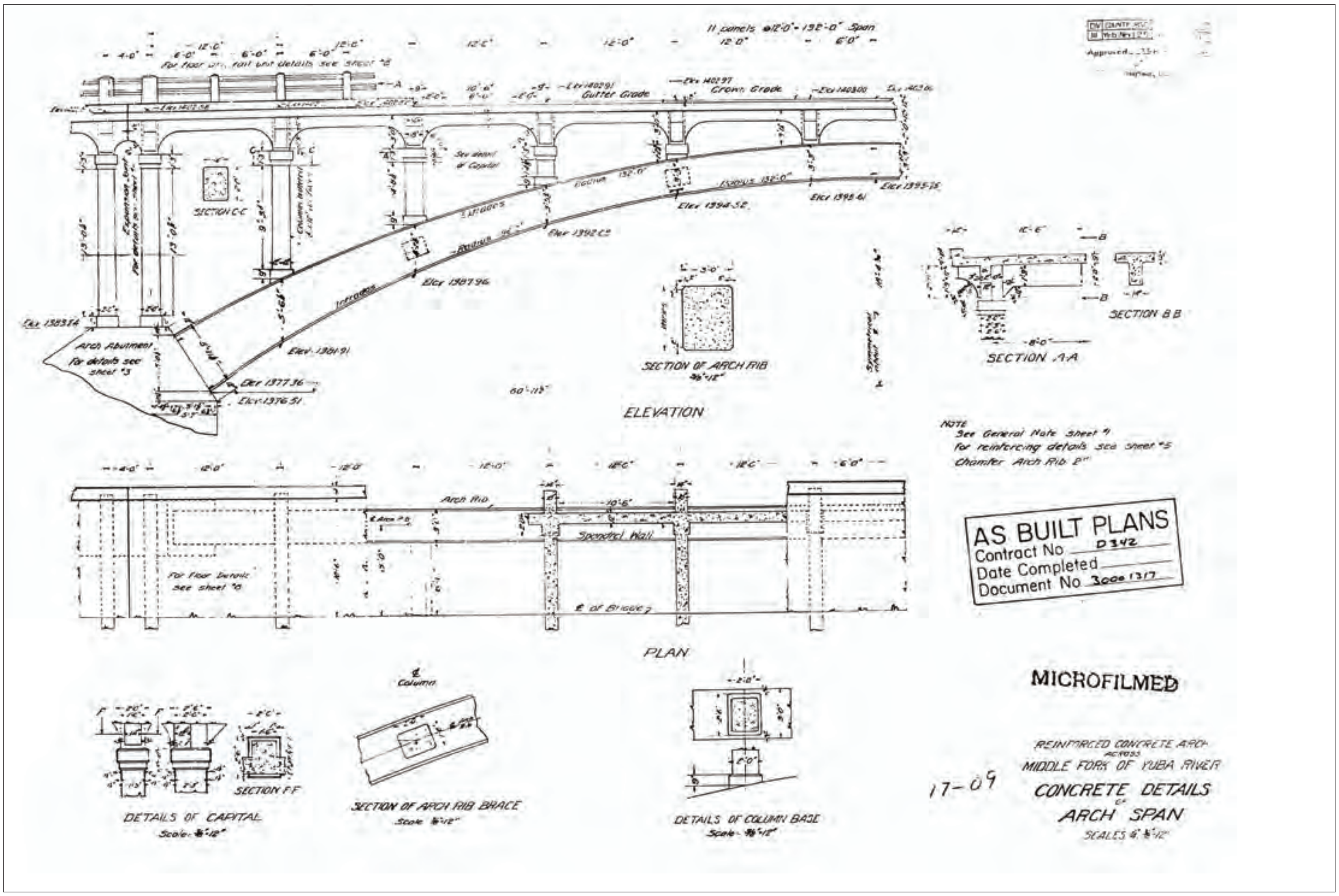

Fig. 4. Freeman's Crossing Bridge, Nevada County, California, construction documentation, 1920-1921, HAER CAL,29-SANJUN.V,1. This drawing shows a reinforced-concrete arch whose primary proportions were probably determined by appeal to empiricist formulas.

compressive stresses.[15] In contemporary engineering analysis, the stress distribution assumed at the ultimate load on the beam is parabolic, rather than triangular. However, the assumption of a linear strain, which is carried over from wood and steel design, can be justified only by appeal to empirical details.[16] In the cracked section, the strain is concentrated at the cracks; in between cracks the concrete is relatively strain free. Between the cracks, the section is stiffened by the tension in the concrete. Similarly, the stress in the reinforcement varies, being the greatest at the cracks and the least in between cracks. In beams in buildings, there is considerable arching action due to the restraint of the beam at the supports and to the reinforcement acting as a tie. This results in a strengthening of the beam beyond the strength predicted by pure bending. These are examples of the empiricist corrections that have to be made in order to justify rationalist elements of contemporary design practices, mentioned at the end of example one above. Moreover, the rationalist determinations of the tensile steel area and the stirrup size are only a small part of the decisions made in the design of a reinforced-concrete beam. Figure 5 depicts an early reinforced-concrete beam to illustrate the additional decisions made in the design and construction of this beam, including concrete cover over reinforcement, bend points, haunching of the beam, and choice of stirrup spacing. These differences, rather than any analytical method, formed the differences between the differing systems promoted by Wayss, Hennebique, and other late nineteenth-century promoters of a system of reinforced-concrete construction.

The first procedures for the design of concrete structures were undoubtedly empiricist in method. The procedures used by Coignet, as explicated by Quincy Gillmore, use proportions rather than any rationalist basis for the design of the early unreinforced-concrete structures. Gillmore describes the construction of a six-story house for which the bearing walls increase 1 inch in thickness for each floor and in which a flat arch is provided in the cellar with a span/rise ratio of 10.

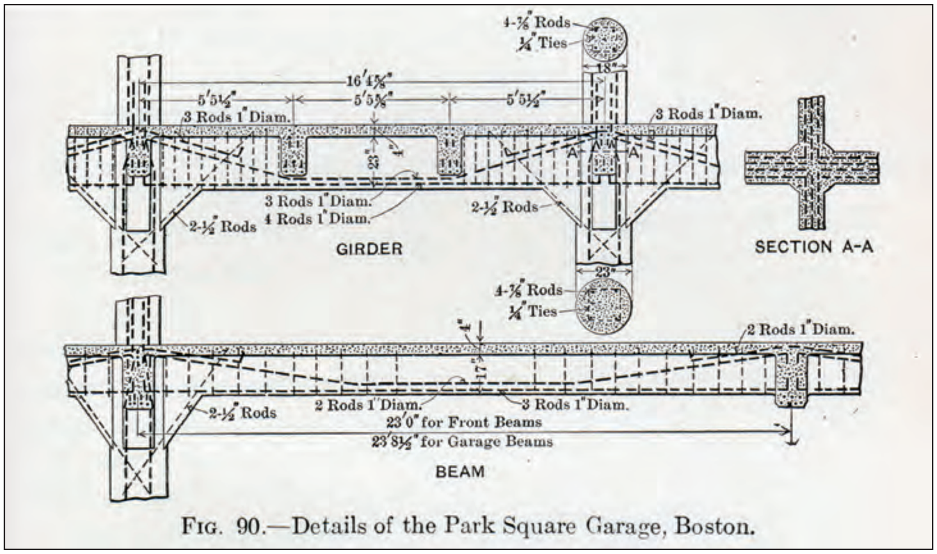

Fig. 5. Reinforcement layout for a reinforced-concrete beam, from F. E. Turneare and E. R. Maurer, *Principles of Reinforced Concrete Construction* (New York: J. Wiley and Sons, 1907), 53.

In discussing his designs for terraces, Coignet describes the application of span-thickness ratios for floors.

> To build a floor or a terrace in concrete, small iron beams shaped as a double T are placed on the walls. The depth of these beams is proportioned based on the span of the floor…
> A span of four meters requires beams eight centimeters in depth
> Five meters requires twelve centimeters
> Six meters requires sixteen
> Seven meters requires twenty
> Eight meters requires twenty-four. [17]

Jackson advances an empirical rule for the design of reinforced-concrete beams. Jackson's rule takes the form

$$SL = \frac{ADC}{L}$$

where *SL* is the total safe load in tons, *L* is the span in inches, *A* is the area of reinforcement (20 lb/yard rails), *D* is the depth from top of floor to bottom, and *C* is an empirical constant (50–60) representing the strength of the reinforcement.[18] In this formula, many of the complications of the Bernoulli-Euler formula are omitted, and the fulcrum for the moment of the tension reinforcement is supposed to be at the compression face of the beam.[19] This formula can be recognized as empirical through its mixed length and weight units and its use of an empirical constant.

Conclusion

A historical review of the design methods used for reinforced concrete indicated three main findings. First, the review highlighted some weaknesses of design approaches that appeal exclusively to rationalist models. Second, it documented the ubiquitous role of empiricist elements in design. Third, it showed that the ubiquity of empiricist elements is inevitable, as these elements are often needed to correct the idealizations required by rationalist-design methods.

With respect to the first finding, examples of weaknesses in some rationalist models in terms of, for example, computational speed, were described. Empiricist approaches in those cases were more attractive. The primary example of this finding is the design of concrete arches: several rationalist theories were available to late nineteenth-century designers, but most designers preferred to use empiricist formulas. Additionally, effective empiricist approaches to structural design preceded the development of a rationalist procedure for accomplishing this design. Two examples were discussed: Coignet's successful design of terraces before any apparatus was in place for the rationalist design of such structures, and Perret's use of thin shells before the development of a rationalist theory for thin-shell structures.

Secondly, the historical review made particularly clear that commitments to empiricist approaches were commonplace and that structures designed according to empiricist principles performed as well as those contemporary structures designed according to rationalist principles.

The findings further indicated that while the design of reinforced-concrete structures moved from an explicitly empiricist approach in the mid-1800s to a more rationalist approach by the 1900s, implicit appeals to empiricist methods often remain, and for good reason. The example of Perret's reinforced-concrete structures built in the early 1900s illustrates that it is possible to note implicitly empiricist decisions and elements of empirical design even in explicitly rationalist procedures. Because idealized rationalist models make use of false assumptions, empirically based corrections to these assumptions are needed when the models are applied to particular cases.

Fig. 6. Francois Coignet House, Brooklyn, New York, built 1872, looking west, 2016. Photograph by Trix Rosen.

Finally, the discussion was informed throughout by the details of philosophical debates between rationalists and empiricists. These philosophical details provide a useful context for examining the debates as they play out in engineering.

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Notes

1. The Wisconsin Avenue Bridge in Georgetown, Washington, D.C., for instance, was strengthened with drilled-in grouted internal anchors, because the engineers were unable to determine an appropriate load rating analytically (apparently no accepted rationalist-analysis method for a stone arch exists), without visual evidence of structural deficiency. See https://www.fhwa.dot.gov/publications/publicroads/05mar/07.cfm, accessed Jan. 16, 2017.

2. Francois Coignet, *Bétons agglomérées appliquées à l'art de construire* (Paris: E. Lacroix, 1861). See also Q. A. Gillmore, *A Practical Treatise on Coignet-béton and Other Artificial Stone* (New York: D. Van Nostrand, 1871). For a good introduction to the life and work of Joseph Monier, see also J. L. Bosc et al., *Joseph Monier et la naissance due ciment armé* (Paris: Editions du linteau, 2001).

3. E. Ast, "Das System Hennebique," *Zeitschrift des Oesterreichischen Ingenieur und Arkitekten Vereines* 52:13 (March 1900): 209-214. See also W. Ritter, "Die Bauweise Hennebique," *Schweizerische Bauzeitung* 33-34 (1899): 41-43, 49-52, 59-61. See also G. A. Wayss, *Das System Monier* (Berlin: A. Seydel, 1887).

4. American Concrete Institute, *Building Code Requirements for Structural Concrete* (Farmington Hills, Mich.: American Concrete Institute, 2014). See, for example, Table 9.3.1.1.

5. René Descartes, *A Discourse on Method,* trans. Donald A. Cress (Indianapolis, Ind.: Hackett, 1993).

6. David Hume, *An Inquiry Concerning Human Understanding* (Cambridge: Cambridge Univ. Press, 2007).

7. Paul Frankl, "The Secret of the Medieval Masons," *Art Bulletin* 27 (1945): 46-60. See also Jacques Heyman, *The Stone Skeleton: Structural Engineering of Masonry Architecture* (Cambridge: Cambridge Univ. Press, 1995). See also Salvatore DiPasquale, *L'arte del costruire: tra conoscenza e scienza* (Venezia: Marsilio, 1996).

8. Bernard Champigneulle, *Perret* (Paris: Arts et métiers graphiques, 1959): 19. "Les Perret...affirmaient par l'exemple l'utilisation économique et rationnelle du béton [The Perrets...affirmed by example the economical and rational utilization of concrete]. This use of the term "rationalism" is not to be confused with philosophical rationalism. French rationalism in architecture, inspired by Viollet-le-Duc's interpretation of gothic architecture, holds that all architectural elements of the building should be adapted to their use in resisting loads.

9. Franz Dischinger, "Schalen und Rippenkupeln," in *Handbuch für Eisenbetonbau,* 3rd ed., ed. Fritz von Emperger (Berlin: 1928), 12, 151-371. See also David Billington, *The Tower and the Bridge* (New York: Basic Books, 1983), 173.

10. Nancy Cartwright, *How the Laws of Physics Lie* (New York: Clarendon, 1983), 13.

11. W. J. M. Rankine, *A Manual of Civil Engineering,* 12th ed. (London: C. Griffin, 1876). This book includes both rationalist methods for the interpretation of arch behavior and empirical rules for arch design. The empirical rules are derived, in part, from some of the rationalist formulas. See also M. A. Howe, *A Treatise on Arches* (New York: John Wiley and Sons, 1897).

12. C. Trautwine, *The Civil Engineer's Pocket-Book* (Philadelphia: Claxton Remsen and Haffelfinger, 1874). Trautwine's rules are strictly empirical, derived from observation of completed arches. See also Paul Séjourné, *Grandes voûtes* (Bourges: Tardy-Pigelet, 1913). See also J. R. Perronet, *Déscription des projets et de la construction des ponts* (Paris: Didot, 1788).

13. E. S. Gould, "Proportions of Arches from French Practice," *Van Nostrand's Engineering Magazine* 29 (1883): 449-469.

14. Bridge data is available in the HAER Collection at the Library of Congress (HAER CAL,29-SANJUN.V,1–17) and at http://hdl.loc.gov/loc.pnp/pp.print, accessed Nov. 30, 2016. The bridge was demolished in 1993.

15. F. E. Turneaure and E. R. Maurer, *Principles of Reinforced Concrete Construction* (New York: J. Wiley and Sons, 1907), 53.

16. According to ACI 318-14, R22.2.1.2, "Many tests have confirmed that it is reasonable to assume a linear distribution of strain." It appears to be understood that this is an assumption, not wholly justified by experimental evidence.

17. Pour faire un plancher ou une térrasse de béton, on pose sur les murs, également de béton, des poutrelles de fer à double T; la force, la hauteur de ces poutrelles sont porportionnées à la portée des planchers; ces poutrelles sont fendues et ouvertes a leurs deux extrémités, de manière à former tirant.

Une portée de quatre mètres exige des poutrelles de huit centimetres de hauteur
Cinq mètres exigent douze centimetres.
Six mètres en exigent seize.
Sept mètres en exigent vingt.
Huit mètres en exigeront vingt-quatre.

18. P. H. Jackson, *Improvement in Building Construction: Mainly Relating to Artificial Stone and Concrete and Portland Cement* (San Francisco: P. H. Jackson and Co., c. 1897), 17. Similar rules are advanced in E. Thacher, *Diamond Bars for Concrete-Steel Construction* (New York: Concrete-Steel Engineering Co., 1908), 22-23; and F. H. Kidder, *The Architects and Builder's Pocket-Book* (New York: Wiley and Sons, 1904), 867. Considering a 6-inch-thick floor (d = 6") made of 3,000 psi concrete, spanning 6 feet, and using new 20-lb steel rails at 24-inch spacing (C = 60; A = 1 in^2/ft) gives a safe unit load of 5 lb/in or 120 lb/ft^2. A similar modern working stress analysis gives a very similar result.

19. This is very similar to Galileo's model of beam bending, in which the bending is caused by an external lever, and the resting moment is due to the moment of the resistance acting about a fulcrum in the compression face of the beam. See Galileo Galilee, *Dialogues Concerning the Two New Sciences* (New York: Macmillan, 1904).

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