**Ars sine scientia: how incorrect design theories lead to correct designs**

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1. **Introduction**

Well before the construction of the Duomo in Milan, and well after, builders have used falsifiable or falsified theories for the sizes and configurations they chose for their structures. While including iron ties in their arches from the beginning, the builders of the Duomo asserted in 1400 that the pointed arches exert no thrust on their supports. The attendees of this conference will be able to verify that this false premise has produced an enduring structure. In a similar fashion, a modern engineer may insert mesh reinforcing in a structural slab and assume in design that the reinforcement will remain in the middle of the slab—a patently incorrect assumption. However, this practice is validated by decades of acceptable performance of concrete slabs constructed in this manner.

To understand the history of such false assumptions is to make significant progress toward the effective preservation of historic structures. A contemporary engineer does not possess moral standing for imposing a modern theory of the behavior of structures on a structure designed according to an earlier theory. The error is greater if this modern understanding is used to determine strengthening requirements. Instead, it is critically important to understand within a cultural, technical, and historical context the approach taken by the original designers and builders of the structure, and to form an understanding of the strengths and deficiencies of the structure within this context.

2. **Incorrect theories, correct structures, or correct theories, incorrect structures?**

To introduce this topic, I present a few examples concerning the kind of manifestly incorrect notions of structural design and behavior that our buildings have been subjected to over the centuries. The first example, from the 14th century construction records of the Duomo of Milan, is possibly the best known, surely here in Milan at least. It involves the only recorded debate from the Middle Ages over the theory of structures—for all the documents available over the course of the twelfth through the fifteenth centuries, this is the only one where the actual structure of the building in question is under debate. In 1399, a group of three French experts were engaged, including the contentious Jean Mignot, presumably to determine the readiness of the supporting structure for vaulting. Mignot immediately declared that the structure was threatening ruin and when nobody in the cathedral works would listen to him, appealed to the Duke. Mignot's list of 54 faults or 'doubts' is presented on 11 January 1400, along with the responses of the Milanese architects. In a further council on 25 January, Mignot elaborates on his main objections: the four towers intended to sustain the tiburio at the crossing are not built with sufficient foundation or piers and the buttresses around the chevet are inadequate.
In the earlier meeting, in defense of their chevet scheme, the Milanese architects make the statement that «pointed arches do not exert a thrust on the buttresses.» Having had some time to think about this, Mignot counters two weeks later. 

«...and what is worse, it has been rebutted that the science of geometry does not have a place in these matters, because craft is one thing and theory is another. The said master Jean says that craft without theoretical knowledge is worthless, and that whether vaults are round or pointed, if they don’t have good foundation, they are nothing, and nevertheless when they are pointed, they have the greatest thrust and weight.» [Annali, 1877, 209, See also Ackerman, 1949, 100].

The response of the Milanese architects to this statement was that, in addition to an adequate foundation to their arches, which may well mean adequate provisions against lateral thrust, they have added ‘strictores ferri magni,’ great iron ties. So, to guard against the thrust, which in their theory may not exist, the Milanese engineers had the knowledge to include iron ties. While theoretically deficient, their notion of how to build is entirely correct.

The second vignette concerns the two Guastavinos, Rafael the elder and Rafael, Jr. The father, in the late 19th century, imported the idea of a vault composed of layers of flat tile from Italy via Spain to the US. These men, by profession builders rather than engineers, asserted in technical treatises that their vaults, especially those with double curvature, did not exert thrust on their supports, a claim that they justified by citing the cohesion of their vaults compared to a vault built with voussoirs set in non-cohesive cement [Huerta, 2003, 112; Guastavino, 1892; Ochsendorf, 2009]. However, much like the Milanese engineers a half a millenium earlier, they inserted iron ties into their vault to ensure that they remained stable in the face of the non-existent lateral thrust. Ira Osborn Baker (1907, 455) reserves the most scathing criticism that a science-minded, late nineteenth century engineer can muster for the method of finding the correct line of thrust in an arch by the ‘least pressure principle.’ Baker calls it a ‘meta-physical principle’ meaning, to a positivist, that it is outside of the purview of verifiable truth, therefore in the realm of any other non-verifiable propositions, such as the existence of the soul or the reality of sensible objects. On the other hand, dozens of successful arch structures have been designed on the basis of this principle.

Until very recently, the design codes for wood, masonry, steel, and for general loading permitted an increase in allowable stresses of 1/3 for load cases involving wind or earthquake. (ACI 530, 1999, C-16) (UBC, 1982, 2303(d), 125) No defensible theoretical justification has ever been advanced for this provision: the lack of justification has evidently caused its removal from contemporary codes. However, again, thousands of competent structures have been built according to this rule.

In our time, we design one-way concrete slabs according to a particular set of unwritten rules. It is normal to treat multiple spans as a single simple span, uniformly loaded, and to design reinforcement on the basis of the reinforcing being placed at mid-depth of the slab. In practice, none of these assumptions is justifiable, however, slabs continue to be designed and built on this basis,
behaving as multiple spans, subjected to non-uniform loading, with the reinforcement trodden to the bottom.

A recent review of a masonry bridge in the Washington DC area produced the result that the bridge was deficient [Darden and Scott, 1985]. This is almost exactly the opposite scenario of the four cases given above: instead of an incorrect method applied to the production of a competent structure, a competent structure is analyzed and an incorrect conclusion is reached: the structure needs to be reinforced. While the former strategy underlies much of modern construction, the latter is usually used as a means for the substitution or removal of historic fabric.

On the other hand, abundant examples are available of rationally determined engineering strategies that don’t work. Many of the examples are from the field of earthquake resistant design. Strategies, such as the ‘pre-Northridge connection’ [Bonowitz and Youssef, 1995] or the ‘energy-absorbing soft story concept’ [Fintel and Khan, 1969] may have made sense for the dissipation of seismic energy, but have not worked in practice, due to brittle fracture in the first case, and due to issues with post-earthquake occupancy in the latter case. Each of these cases of failure is subsequently added to an experience bank and re-applied to the development of more effective strategies.

The process, which is on-going in earthquake-resistant design, of finding theories wanting in practice and re-working them for future construction, can be alternatively interpreted as an instance of the scientific method, or as an example of trial and error. When applied in modern times, it is generally considered scientific, while, when speaking of medieval or Roman architecture, it is invariably dismissed as trial and error.

3. A brief note on the application of theories of knowledge to the design of structures

To begin to understand the intellectual context of the application of reason to the design and assessment of structures, it is worth a very brief and very preliminary incursion into ideas about how knowledge of the universe is acquired. The two opposite poles of the philosophy of knowledge are rationalism and empiricism.

According to the doctrine of rationalism, knowledge of nature is found through reasoning. Prominent rationalists have included Rene Descartes (cogito ergo sum). An important medieval rationalist is Thomas Aquinas, who based his work on the teachings of Aristotle. Aristotle, for instance, deduced solely by reasoning that all motion must be initiated by a fixed, indivisible, incorruptible, eternal Prime Mover. Aquinas identified Aristotle’s Prime Mover with the Christian God. This is the essence of the rationalist outlook: that all phenomena of nature, and theology itself, can be demonstrated by reasoning.

An empiricist such as David Hume or George Berkeley, on the other hand, considers that there is a severe limit to man’s ability to understand natural phenomena: only through experience is it possible to see that one phenomenon is connected to another (a billiard ball striking another, for instance), but that we have no capacity to explain or to reason how this happens. For the objects of experience, we can only identify connections and causes through
observation, and have no capacity to go further.

It is possible to connect the ideas of rationalism with the scientific approach to engineering, in which we construct analytical models that allow us to deduce the causes of phenomena of strength, stability, failure, and collapse, and in turn to design better structures. Empiricism is more directly associated with empirical design, in which we simply size structures on the basis of past experience, without needing to identify the underlying phenomena that make them work. In the present discussion, the theorizing of the French masters at Milan, or the proponents of finite element analysis are primarily rationalist in outlook, while the Milanese masters, or those who declare an undamaged 500 year old structure safe without further investigation are displaying an empiricist outlook.

A further necessary idea concerning the application of science is the doctrine of conventionalism, that there is no absolute truth in the structure of our observations of nature, but that we adopt conventions that describe the logical foundations of our investigations. Conventionalism is frequently applied in the modern conception of mathematics, where one set of axioms (such as non-Euclidean geometric axioms) is no better than another (such as the Euclidean axioms), but that the logical structure of a portion of mathematics departs from an almost arbitrary set of axioms. The ideas of conventionalism seem to be almost directly applicable to engineering—there are certainly grounds to refute the Bernoulli-Euler theory of bending of a beam, especially for a reinforced concrete beam, but we persist in applying this theory to reach productive conclusions about beams. So, when we size reinforcement in a concrete beam on the basis of ‘plane sections remain plane,’ we are accepting ideas that can be readily falsified in an experiment on a cracked section. However, our experience has indicated that useful results about the reinforcement of beams can be obtained using this theory. In undertaking preservation works, we can further recognize that although the theories that were used in the Middle Ages or the nineteenth century may have been similarly false, but that they have been used in a similar fashion to modern theories to achieve productive results about the structural design of a building.

4. An argument for leaving historic structures alone

I hope that one thing is clear from the preceding discussion—that we don’t know more about the behavior of the historic structures under our care than their authors did. In many cases, our way of understanding these structures is substantially different from the understanding at the time of the production of the structure, however nothing is gained from imposing a strictly modern outlook on these structures. The result of such overanalyzing, overengineering, and overly modifying historic structures is inevitably the loss of historic fabric, in the best case, and the loss of the integrity of the structure in the worst case. I have seen far too many masonry arch bridges rebuilt from the inside out or unnecessarily reinforced in my brief career. Often these bridges showed no worse damage than spandrel walls separating, but this type of event prompted their custodians to declare the arch itself incapable of carrying load, and requiring a new concrete bridge to be constructed within the masonry bridge.
A better approach in general was taken on a small county-owned bridge in Pennsylvania, which did have load-rating problems. The fill was removed, replaced with an engineered material, and backing masonry was installed behind the arch ring, completely consistent with nineteenth century practice. The rehabilitation of this bridge is described in more detail in an AASHTO-published document [SRI Foundation, 2011, 3-6].

In a similar instance for a wrought-iron bridge, in Pennsylvania, the Pennsylvania Department of Transportation and its consultants were determined to preserve the Pine Creek lenticular bridge. The panel points of the truss of this bridge were designed in 1889 for live loading of 6.7 tons (60 kN), which compares to the full [not divided between two trusses in the single-lane bridge] AASHTO lane loading of 6.6 tons (60 kN). The truss chords were designed for approximately 7 tons/in² (97 MPa), which implies a safety factor between 2.5
and 3. However, any of the original conceptions of the design of the structure were discarded during the 2010 rehabilitation. In order to achieve a full 20-ton (190 kN) load rating according to a contemporary interpretation of a contemporary code, all tension members were removed and replaced with modern material, while the area of the top chord was almost tripled by the addition of a 2 inch (50 mm) thick steel cover plate. The forged eyebars used in the bottom chord bore the irregularities and hammer markings of a custom-forged product, while the new members, fabricated by water jetting show no such irregularities. The hangers for the floor system, originally square bars upset to a circular cross section (Fig.3) to receive threading, were replaced with a system with no historic authenticity at all. In a final irony, the Pennsylvania DOT has retained the 10 ton posting of the bridge, and will not allow larger trucks to cross the structure, even for testing. Examples of better practices are available in Pennsylvania. The quintuple intersection Warren truss bridge at Slate Run, PA (HAER 2013) was simply considered adequate for road traffic primarily on the basis that it originally served as a rail bridge, and the final outcome has greater historic integrity than the Pine Creek Bridge.

5. Conclusions
The empirical nature of engineering activity results in a disconnect between rational theory and experience with a structure. While the engineering profession has historically assigned a greater value to empirical knowledge, the contemporary engineering profession appears to value rational analysis more highly. A more balanced view of engineering—its scope, its methods and its achievements—would assign a greater value to the observations that result from experience and would not demand that such observations be applied in a scientifically consistent manner. Incorrect theories that result in correct structures would be recognized for their value in distilling and organizing empirical observations while scientific theories that had not received significant testing on structures would be recognized as suspect.
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