The Origins of Reinforced Concrete and the Technological Nature of Design Thought

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For many years, architectural technologists have been fighting to regain status in architectural education in the United States. One of the difficulties is that technology is often thought of as deterministic by designers and equated with what they consider a relatively unattractive field, science. The decade of popularity enjoyed by the "ACSA Tech" conferences and their development to the premier research forum of that body disabused many of that fallacy. However, technology has still not quite insinuated itself into the purview of many designers as design itself, while in many respects technological and design thinking are parallel if not identical. The material for this paper is taken from a book that deals more extensively with this topic in a number of ways: "Building the Nineteenth Century," due to appear with MIT Press in May 1996.

TECHNOLOGICAL THOUGHT

All builders, whether architects, engineers or contractors, appear to use a comprehensive form of "soft technology." This is a form of technology quite distinct from the generally accepted "hard" form based on physical and mathematical analysis that is generally taught in builders' curricula. What I mean by "soft technology" is that form that we use to *make* objects, not to *analyze* them. This "soft technology" is a balancing act where the ideal, abstract field of design meets the pragmatic, sometimes frustrating realm of the process of making a three-dimensional reality. The thought-form that corresponds to this ambivalence is one which aims at making objects. I call this "technological thought" and I believe that it is the premier thought form that we use in our culture to attack new problems.

C. P. Snow's analysis of what he saw as "two cultures" in the Western world describes a gulf between literary or humanistic and scientific thinking.[1] His study fell on fruitful ground and was translated into many languages. Snow was right. There is a great divide between these two modes of thought in our culture. But there is an even greater one that concerns us even more closely as architects, and that is the chasm between science and the humanities that analyze on the one hand and technology that makes on the other. This gulf appears insurmountable at first blush. It separates builders from analysts and leads to all sorts of grotesque misunderstandings. But isn't this apparent dilemma precisely where our work as architects really lies?

The world of design and technology uses language differently than science: When designers and builders say "detail" we mean "small-scale problem" and not "subordinate part," like humanists and scientists do. Every builder is well aware that a detail problem can often be more crucial to a structure than the system as a whole. And the word "system" changes its meaning too from the "ordering principle" of science to "functioning object" or "building set" in technology.

Analytical thinking is concerned with abstractions, that is with concepts, hypotheses and theories and makers with objects. Analysts think within the framework of the hierarchical system of scientific method, vertically to use Edward de Bono's term. Makers are "lateral" or associative thinkers who think in non-hierarchical matrices. The goal of science and the humanities is to attain knowledge or insight while technologists and designers want simply to make functioning objects. The appropriateness of a technological method lies in the functioning of the finished object and not in its logic. A builder is rarely interested in the methodology of knowledge or epistemology. Scientists and humanists research analytically. Technologists do that too, but they do more. They add a form of intuitive matrix thinking, and the resultant hybrid thought form is more flexible than either of the two components. Antoine Picon has characterized this as a preoccupation with "movement."[2] It can also be characterized as a form of unstable intellectual equilibrium, a dialectic between the two components that works to create useful solutions. This form of thought is one of the great advantages of technological thought and it explains its popularity in our age. However, only those who practice this mode of open or freewheeling thought realize this. All others see only a danger of "polluting" their own, exclusive thought form.

THE DEVELOPMENT OF TECHNOLOGICAL THOUGHT IN CONCRETE

An early instance of this dynamic, hybrid thought form was

John Smeaton's analysis of hydraulic mortar in 1756.[3] Smeaton was the first to use the title "civil" as opposed to military engineer. He was also the first to analyze hydraulic mortar chemically. Smeaton was familiar with the existing literature on the subject, like Belidor's book in French or the reports of Sir Christopher Wren.[4] He also knew his Vitruvius, but these sources were insufficient for him because they failed to explain what it was that made the mortar hydraulic.

As he designed the Eddystone Lighthouse for an especially exposed site on the southern English coast, he analyzed several hydraulic cements with the help of the potter and chemist William Cookworthy.[5] They found to their surprise that it wasn't the purest or hardest limestone that gave the best hydraulic characteristics, as everyone had believed since Vitruvius. The stone needed an impurity of silicates or clay to make it work.

Nothing could explain the effect this impurity had at the time, neither the traditional thought modes of the Western world that based on the theological concepts of purity and faith, nor the analytical logic of the new breed of "natural philosophers" that would gradually lead to scientific method. But chemistry could at least demonstrate that it worked. Chemistry was not yet a "natural philosophy" at the time. It was still strongly influenced by the medieval alchemist tradition, and chemical engineering that was then in its infancy, lived from the creative mixture of analytical insight and empiricism that we today associate with technological thought. We have no way of knowing how this discovery influenced Smeaton's engineering designs, but his realization influenced subsequent research into hydraulic cements.

Cookworthy was an artist and technologist. Pottery, glazing and chemistry were closely connected "arts" at the time. Smeaton was a physicist, mechanic and builder. Both were intellectual border-crossers in a period in which modern scientific method was being formed. They were both clear about the differences between faith and provable data, but certainly not about the distinction between scientific and technological thinking. Nor would the distinction have meant anything to them. We project the thought mode they were inventing a posteriori into their world in order to trace the first signs of a development that would crystallize a century later.

Nevertheless, Smeaton and Cookworthy's analysis was not unique. Charles Stanhope, Viscount Mahon read a report to the Royal Society in London in 1778 on fireproofing buildings.[6] He had built and burnt two identical houses, one with what was then standard construction and the other protected by a layer of horse-hair reinforced plaster. Mahon was a physicist, not a builder. His field was in the throes of developing scientific method and he crossed the border between physics and construction in order to apply experimental methods to the problem of fire-proof construction.

His pragmatic, and therefore "technological" work differed from that of the early engineering theoreticians like Giovanni Poleni, Charles Augustin Coulomb or Leonard Euler, all of whom applied already existing mathematical theories to building problems because they found them to be practical applications for their abstractions.' Technology was for them an application of their scientific interests. But Mahon's experiments were neither clothed in mathematical abstraction nor were they an application of something else, and that made them new. Like Smeaton, Mahon went the opposite way and sought and used appropriate methods wherever he found them to solve his practical problems. He inverted the relationship between science and technology. The technological problem was primary and the method to solve it secondary. This made Mahon's experiments accessible to every builder.

Between the middle and the end of the eighteenth century men like Smeaton and Mahon began increasingly to use physics to understand structure and materials. What they did and how they did it led gradually to civil engineering theory and material science. Some of them, like Franz Joseph von Gerstner in the Austro-Hungarian Empire and Coulomb in France were builders as well.[8] They too crossed the borderline between science and empiricism and helped establish hybrid thought patterns in building.

The path was by no means an easy one. Other cement researchers like Barthelemy Faujas de Saint-Fond, Antoine-Joseph Loriot, Fleuret, Jean-Antoine Chaptal and Polycarpe de la Faye in France, Bryan Higgins in Britain and several Swedish researchers examined the material from either the analytical or the empirical side.[9] None of them combined both viewpoints in order to gain radically new insight. So it was only Smeaton's results, gained by means of his hybrid, "impure" thinking, that led to a series of experiments that finally resulted in the creation of our modem reinforced concrete.

In 1818, the most influential of these many researchers, Louis-Joseph Vicat, published a first report on the manufacture of an artificial hydraulic cement in France.[10] This publication led to the formation of a group of practically-oriented French researchers who all concentrated on developing artificial products. In Germany, on the other hand, chemists concentrated only on analyzing existing materials and they left practical application to builders and inventors.

Where Smeaton and Mahon had linked analytical method and design, Vicat quite inadvertently clarified the limits of analytical thinking in building. In a report he published in 1831, he proved that hydraulic cement protects iron from rusting." He had cast wires into blocks of mortar and exposed them to the rain. As a result of his excellent results Vicat recommended casting suspension bridge cables directly into their foundations without first attaching them to flat, wrought-iron anchor bars that were less reliable in tension. This recommendation contained a fatal error.

It is true that iron wires do not rust when they are imbedded in cement under laboratory conditions. But when thick bridge cables consisting of many wires are imbedded, the effect is quite different. Cement shrinks as it cures and can separate from thick cables. Bridge cables also vibrate and this can influence the formation of fissures too. Rain water is pulled into fissures by capillary force. This water is caught and does not evaporate easily, and it rusts the iron. Theoretically Vicat was quite right in his observation, but practically his recornmendationspelledcatastropheforFrench wire cable bridges. It led to the collapse of the Basse-Chaine Bridge in Angers in 1850 and the death of over two hundred soldiers.[12] The French government reacted by banning the construction of suspension bridges for twenty years, by which time France had lost her leading role in this type of construction to the United States.

Vicat's problem lay in the concept of scale. In technology, as in most design fields, issues of scale are central to the solution of any problem. Vicat was a structural engineer, but he worked almost exclusively as a building physicist. That is why he neglected to translate his experimental model into a full-scale field test. Analytical models are never reality, they only ***represent*** it in simplified form. Researchers working in abstractions tend to forget this truism all too easily.

While French and German researchers led the way in the analysis ofmaterials and structural behavior, British military academies of the early nineteenth century preferred to pursue the empirical path of full-scale building research. At first the English appeared to be loath to seek abstract, physical principles behind material characteristics. They even left the chemical analysis of the English invention, Portland Cement to the German Max Joseph von Pettenkofer in 1849.[13]

In 1826, the Duke of Wellington, Master of the Ordnance and victor of Waterloo, introduced the study of construction into the royal engineering academy at Chatham. The director, Sir Charles William Pasley designed the curriculum himself. He wanted to orient the subject as practically as possible and took the opportunity to include research on the promising new material concrete. He consulted the physicist Michael Faraday and one of his staff officers who had some familiarity with the new material. Pasley published two research reports in 1830 and 1838 in which he broke new ground.[14]

While German and French researchers concentrated only on the physical characteristics and chemical composition of the basic material cement, the British under Pasley began to test concrete's structural resistance under loading conditions. The French Vicat and Clement-Louis Treussart carefully measured the penetration of weighted needles and blades in fresh and cured mortar and drew their analytical conclusions, Pasley and his followers went another route and shelled concrete vaults to see how well they stood up under impact, and he examined the tensile strength of the material by mortaring a row of bricks horizontally out from a wall until they fell.[15]

None of this was stictly analytical. Pasley's "method" may seem bizarre and uncontrolled to us. It first led to apparently illogical, hybrid constructions. Pasley placed wooden lath and then iron bars into the cement to increase the material's native tensile and bending strength. His procedures are a typical example of what we now call "fuzzy thinking" or imprecise hybrid thought, and it prepared the building world for the development of reinforced concrete.

So by the first third of the nineteenth century scientific method had entered building analysis and researchers were beginning to become aware that it had its limitations. Some, like Pasley were also beginning to combine empirical, associative logic with vertical thinking. In order to follow the path that this preparation took we now have to examine the thought processes of Sir Marc Isambard Brunel. Brunel is chiefly known to the history of technology as the builder of the first Thames Tunnel in London.[16] He was born in France, analytically educated in a naval academy there and empirically trained as an engineer in New York. Most of his mature professional life as inventor and engineer was spent in England. Brunel is an unusually clear example of a cultural and professional border-crosser.

At the beginning of the successful digging of the Thames Tunnel lay Brunel's idea for a tunneling shield. Brunel was known primarily as a gifted mechanical engineer. He had designed and built several successful assembly lines for the British Navy. He then turned his attention to the field of construction. The Russian Tsar had asked him to build a permanent bridge over the Neva in St. Petersburg. As ice floes were a perennial problem, Brunel immediately thought of a tunnel. By chance he observed the action of the feared shipworm in London harbor, which, according to his own anecdote, gave him the idea for his tunneling shield. He translated the information he gleaned from zoology into mechanical engineering. Translations of this type implement "fuzzy thinking" and are typical of technological design processes.

Brunel was a master at using such translations. Like Pasley, he applied them to concrete research. Brunel preferred to examine building components instead of crushing test cubes like Vicat and his group of scientists did. Like Pasley, he built tensile structures and imbedded various materials in them to enhance their tensile and bending capacities. By chance, he observed that of all the materials he tried, only iron bonded with the cement. He also noted that the shovels that the workmenused to mix their mortar and left uncleaned overnight could not be freed of their hardened coating of cement. He combined the two unconnected observations and made a discovery that was in no way the result of a logical, incremental search in the sense of a scientific research program. But serendipity did not make his discovery any less valuable, since it led quickly both to the development of reinforced concrete and to the concept of monolithic structural behavior.

Brunel translated his observations to another problem which then preoccupied him. He had been searching for an inexpensive method to clad the interior of the tunnel with brick. So he asked the two main contractors on the tunnel, to build two opposing brick cantilevers and reinforce them with bands of iron so that he could compare the quality of two different cements. The structure stood for two years from 1832 to 1834.[17] Next Brunel built a brick beam with iron reinforcement and load-tested it to failure.[18] The only thing that prevented Brunel from discovering reinforced concrete then and there was the fact that he was really trying to find a reinforcement for brick and not for mortar. Therein lay the limits of his technological translation process, and it remained for others to take the consequences of his work.

But this was no weakness in Brunei's thinking, he had simply concentrated his translation on one problem and not the one that now seems more important to us. He did apply his experience with iron reinforcement in another, equally original manner. In the midst of building the tunnel he was forced to replace the shield with an improved model. It was difficult work, since the tunnel heading had repeatedly failed before. So Brunel imbedded iron bands at an angle in the earth in front of the shield to stabilize the earth.[19] He certainly was aware that iron did not bond with earth like it did with cement, but he disregarded the fact that his idea was conceptually illogical, tried it anyway and invented the technique now known as "soil nailing."

"Fuzzy thinking" in building is an open-ended process, and Brunel was certainly successful in his attempts to reinforce brick and earth. Although he just missed inventing reinforced concrete, his work inspired Pasley and others to undertake further experiments with reinforced beams. Pasley built several in Chatham in 1837 and John Bagley White and Sons, a cement manufacturer, exhibited one in the Crystal Palace in 1851.[20]

Parallel to this development, Isaac Charles Johnson, White's production manager, discovered a material with far better characteristics than the cements known before.[21] Ever since 1845 White and Johnson had tried with no success to discover William Aspdin's improvements to his father's 1824 "Portland Cement" patent.[22] In 1851 Johnson overcalcinated a load of Joseph Aspdin's cement in a kiln and threw it on the slag heap.[23] A few days later he noticed that the sintered mixture of limestone and clay had not disintegrated in the rain, and he ground it up out of curiosity to try it anyway. The result set and cured more rapidly than any other cement and became much stronger. Now Johnson had a far better product that he had sought; he had found what was to become our modern Portland Cement. His hunch and experiment probably came from the same type of border-crossing thinking that had inspired Smeaton to examine hydraulic mortar a century before. Johnson died a centenarian in 1911 and was thus able to follow the full development of his material.

Builders began using cement reinforced with iron with more or less success. William Boutland Wilkinson invented a real reinforced concrete around 1850.[24] He neglected to publish it, and so his system had no repercussions in the profession. Neither did Joseph Lambot's concrete rowboat.[25] Franqois Coignet had more success as a contractor and he publicized his method in Britain and France.[26] In 1869 he built the Suez Canal lighthouse at Port Said of reinforced concrete and many other buildings besides. Joseph Monier, another inventor, became the figurehead for the German firm Wayss & Freytag in spite of the fact that prior claims led to the later revoking of many of his patents.[27]

All these pioneers became well known, but there is a less known system that explains a little more about technological thought. An English physician by the name of Henry Hawes Fox built a sanatorium near Bristol in 1834 for which he invented a fireproof floor construction of concrete over rolled girders. His contractor James Barrett suggested he patent it which he did ten years later in 1844.[28] Fox died soon after and Barrett developed the system further. He reported to the Institution of Civil Engineers on his work in 1849 and again more extensively in 1853. The Institution considered his work so interesting that they awarded him the coveted Telford-Prize for the latter year.

Barrett had observed that the loadbearing capacity of the construction increased as the concrete cured. He recognized the influence that iron working under tension and the concrete working under compression had on each other. Both Coignet and Wilkinson had spoken of tensile members before Barrett, but the insight that the combination of materials behaved monolithically was his.

The step from composite to monolithic structure was a small one but an important conceptual translation. Wilkinson and Coignet had already taken that step, and many others followed: Wayss und Freytag and Dyckerhoff und Widmann in Germany, Eduard Ziiblin all over Europe, Ernest Leslie Ransome and Albert Kahn in the United States and Franqois Hennebique all over the world.[29] All of them were practitioners who valued theoretical analysis in construction but didn't overvalue it. They knew the advantages and disadvantages of analysis and they tested the limits of design thinking in the new material fully realizing how the two forms of thinking influenced and supplemented each other. As a result many of their early efforts were formally grotesque, but they did push the limits of the new material.

When they had established a first set of formal and structural parameters for the new material and had experimented with methods of making, then and then only did the analytical scientists begin to take the field over. The Prussian building commissioner Matthias Koenen wrote the very first structural analysis of reinforced concrete for Wayss & Freytag in 1886, Paul Christophe followed in Paris 1899, Emil Moersch in Stuttgart in 1902, and Alfred Buel and Charles Hill in the United States in 1904.[30]

CONCLUSION

There are many other possible examples, but the prehistory of the development of reinforced concrete is a useful model for the development of technological thinking in building. Technological thinking became a design mode of thought that operates with a mixture of analysis and association, with translations and with "creative misunderstanding" in perception. This hybrid and flexible form of thought is incomprehensible to the older forms ofphilosophical and theological thought in Western civilization, and conceptually unclear to adherents of the younger form of scientific thinking.

It spans the gap in which the architect is at home, the gap between the archetypal forms *genesis* and *logos*, between *homo* faber and *homo sapiens*. Indeed, even scientific thinking in our own century has adopted a great deal from technological thinking and gained in flexibility thereby. Insight is valuable in thinking. There is nothing new without insight. With all his fascinating inventions, Brunel lacked the insight to "see" reinforced concrete in what he did. And so it did not exist then. But in building as in so many other technological fields, making is the driving force and the equally necessary obverse of analytical thought. It is this tension between insight and making that creates the new. And that is why technological thought lies at the very basis of our current culture.

NOTES

[1] Charles Percy Snow (1905-c.1982): The two cultures and the scientific revolution, Cambridge GB, 1959.

[2] Antoine Picon: Toward a History of Technological Thought. Technological Systems and Technological Thought. to be published in R. Fox (ed.) Technological Change, OPA, 1995

[3] first published in: John Smeaton (1724-1792): A narrative of the building and a description of the construction of the Edystone Lighthouse with stone London, 1791

[4] Bernard Forrest de Bélidor (1697-1761): Architecture hydraulique , 4 vols. Paris, 1737-1753; Wren's (1632-1763) works mentioned in his nephew's book: Christopher Wren: Parentalia London, 1750

[5] William Cookworthy (1705-1780)

[6] Charles, Vicount Mahon, later Lord Stanhope (1753-1816) in Phil Trans. Roy. Soc., session of 26 Sept. 1778

[7] Marchese Giovanni Poleni (1683-1761): Memorie istoriche della gran cupola del Tempio Vaticano, Padua, 1748; Charles Augustin Coulomb (1736-1806): Essai sur une application des regles de maximis & minimis a quelques problemes de statique , in Mem. Acad. roy. des Sciences, Paris, (1776), vol. 7, 1773, pp. 343-382; and as one example: Leonhard Euler (1707-1783): Sur la force des colonnes, Mem. de l'Acad. roy. des sciences et belles lettres, Berlin, (1753), vol. 13, p. 252

[8] Gerstner (1756-1832) was one of the founders and professor at the Polytechnique of Prague and the builder of the first Austrian, Russian and Polish railways.

[9] Barthelemy Faujas de Saint-Fond (1741-1819): Recherches sur la puzzolane Grenoble, 1778; Antoine-Joseph Loriot (1716-1782): Mémoire dur une decouverte Paris, 1774; Jean-Antoine Claude Chaptal (1785-1782) was one of France's most eminent and prolific chemists; Polycarpe de la Faye (Recherches sur la preparation Paris, 1777 ; Bryan Higgins (1737?-1820): Experiments and observations London, 1780

[10] Vicat (1786-1861): Recherches experimentales Paris, 1818

[11] Vicat: Ponts suspendus en fil de fer sur le Rhône, Annales des Ponts et Chaussees, 1831, vol. 1, pp. 93-145, pl. 3

[12] Arsene Emile Juvenal Dupuit (1804-1866) : Rapport de la commission d'enquête , Annales des Ponts et Chaussees, 1850, 2e. sem., pp. 394-411

[13] Pettenkofer (1818-1901): Ueber die Unterschiede zwischen den englischen und den deutschen hydraulischen Kalken. Dinglers Polytechnisches Journal # 113 (1849), pp. 55 ff.

[14] Charles William Pasley (1780-1861): Observations deduced from experiments upon the natural water cements of England Chatham, 1830 ; Observations on limes, calcareous cements, mortars, stucco and concrete London, 1838

[15] Treussart 1779-1843, French military engineer, later general

[16] Marc Isambard Brunel (1769-1849). Richard Beamish (1798-1873): Memoir of the Life of Sir Marc Isambard Brunel, 1862 London; Paul Clements (1927-): Marc lsambard Brunel, 1970 London; Alec W. Skempton & Michael M. Chrimes: Thames Tunnel: geology, site investigation and geotechnical problems. Geotechnique (1994) 44 # 2, pp. 191-216

[17] Clements, op. cit., p. 201; Beamish, op. cit., pp. 284-285; Min. Proc. ICE, vol. 1, (1837), pp. 16-20; The Rudiments of Civil Engineering. Weale's Rudimentary Treatise 13, 1862, 2nd. ed. part 2, Chap. 4, pp. 134-135

[18] George Frederick White (1816-1898): No. 870. Observations on Artificial Hydraulic or Portland Cement Min. Proc. ICE, vol. 11, (1851-1852), pp. 478-510

[19] Skempton & Chrimes, op. cit.

[20] G. F. 'White, op. cit.

[21] Charles Isaac Johnson 1811-1911, later became a producer of Portland Cement on his own.

[22] William Aspdin (1815-1864), see: Cecil D. Elliot: Technics and Architecture, Cambridge MA, 1992. pp. 153/155

[23] Joseph Aspdin (1779-1855), master mason in Leeds, GB pat 5022, Oct. 21, 1824

[24] Wilkinson 1819-1902

[25] Lambot 1814-1887

[26] Coignet 1814-1888

[27] Monier (1823-1906). Peter Collins (1920- c. 1965?): Concrete, London, 1959. p. 60

[28] Henry Hawes Fox (-c.1852), James Barrett (1808-1859)

[29] Züblin 1850-1916, Ransome (1840-1917), Hennebique (1842-1921)

[30] Koenen (1849-1924) later worked for Wayss & Freytag, Moersch (1872-1950) first worked for the same firm and then became professor of civil engineering first at the ETH Zurich and then at the University of Stuttgart.