The creative response to concrete cracking

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ABSTRACT: Cracking in concrete has served as an important influence in the development of structural design. Careful observation and insightful responses to concrete cracking by designers have led to a series of innovative new structural solutions. This progression is illustrated through several specific historical design examples.

1 INTRODUCTION

Judging from the proceedings of your last conference in 2004, we can see that there is little that we can contribute to the many interesting developments taking place in the main subject of your organization. Our contribution will thus be of a very different sort that will treat concrete cracking as an integral part of the history of structural design. It is our hope that the more scientific work that makes up most of your research will prove to be not just useful to designers but will stimulate them to make better designs and to benefit by future collaboration.

Our thesis is that major advances in concrete structures have arisen through designers' contemplation of observed cracking in their own works as well as in the works of their predecessors. The collected record of a series of such contemplations and the resulting improved or new designs will become, we believe, a necessary part of the education both of students and practitioners. The cracking events we will describe are not the results of shoddy workmanship or incompetent designers but in all cases were the surprising defects that well trained and careful engineers made usually following state-of-the-art ideas.

2 THE CLASSICAL PERIOD

The Pantheon in Rome is undoubtedly the greatest concrete structure of the classical period (Figure 1). It is also the first such structure to exhibit substantial cracking which led to a creative design addition as well as to the form of a similar dome nearly half a millennium later (Mark and Robinson, 1993).

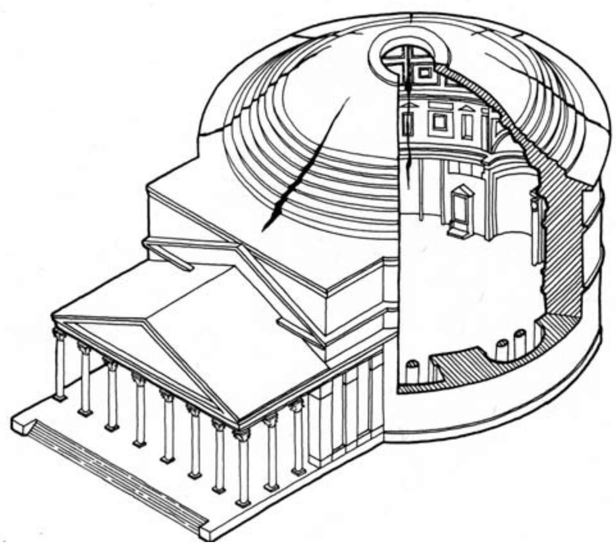

Figure 1. Drawing of the Pantheon.

Constructed between A.D. 118 and 128, the Pantheon is a concrete dome far larger than any earlier such structure. Its 43 meter clear span would not be exceeded in any concrete dome until the 20th century. Made of Roman pozzolan concrete with a lightweight aggregate, the form of the monumental structure had been misunderstood until the pioneering studies of Robert Mark explained it and its influence on later forms. Designed as a hemisphere, the dome was taken to be fully monolithic with concrete rings encircling the dome near its junction with the cylindrical wall. Many students of the Pantheon thought that these rings, clearly expressed above the concrete shells, acted as hoops in reinforcing the shell against circumferential tension stresses. As Mark demonstrated convincingly, these are not rings at all but rather they are extra loading on arches that the Roman builders used to prevent arch bending.

Thus the lower part of the dome is really not a dome but a series of arches separated from each other by radial cracks that extend upwards over half the vertical distance between the hemispherical base and the crown (Figure 2).

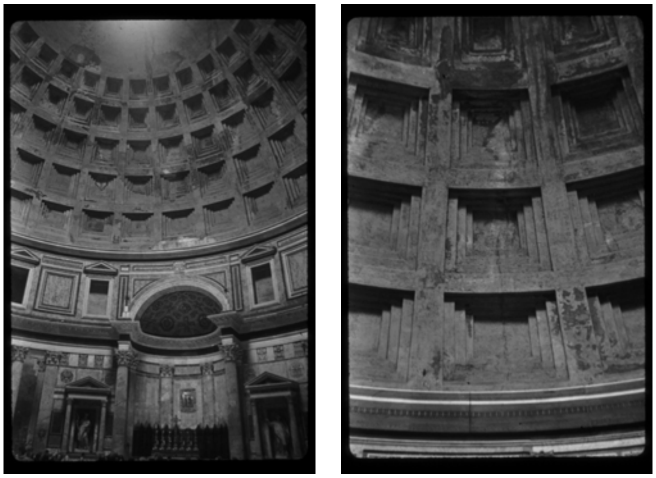

Figure 2. Cracks in the Pantheon.

One can observe these cracks even today nearly 1900 years after completion. The Romans clearly saw them and piled on the extra weight to keep the arches from bending and cracking in the circumferential direction. So the striking ring stiffened form of the Pantheon was a creative response to major radial cracking and the structure has proven durable ever since. The extent of the crack is easily predicted by the simple membrane-theory formula for hoop stresses.

$$N_\theta^1 = aq\left(\frac{1}{1+\cos\phi} - \cos\phi\right)$$

where a is the dome radius in meters, q the dead load in Kg per meter squared, and ϕ is the angle between the axis of rotation and a radius defined by any point down the meridian. Thus when ϕ is greater than $51^0 50^1$ the N_θ^1 will be positive hence tension so that the crack could extend up the shell to a vertical distance of greater than $a/2$, which we can observe even today. In that case it is more than likely that the builders of the Hagia Sophia in Constantinople would have studied the Pantheon as the only extinct dome of nearly the same size as their planned work to the east.

The structure was built quickly between A.D. 532 and 537 but its great dome fell in 558 following the two earthquakes of 553 and 557. Right away a new and higher dome began and was completed between 558 and 562. Despite subsequent partial destruction in earthquakes, that 562 dome is what can be seen today (Mark and Robinson, 1993).

A most striking feature of the Hagia Sophia is the array of windows around the base of the dome which from inside gives the impression that the dome floats on light. While this ideal may have been in the minds of the architects it is nearly certain that the builders intended these openings also to reflect the fact that in a non reinforced dome there would be meridional cracks which the window openings replace. In fact these openings extend above the hemispherical plane to an angle just over 50° between the axis of rotation and the meridional point when the windows end. Thus the remarkable floating feeling is in reality a creative response to the meridional cracking at Rome. The windows are formed by arches that support the great dome so that the defect at Rome became the stimulus for a glorious form at Constantinople 430 years later.

3 THE GOTHIC PERIOD

There are at least two examples of cracking in the great churches of northern France, one of which led to a clear creative response by the designers. Again this is the work of Robert Mark in discovering this example and illustrating it in engineering terms in reaction to a deep misunderstanding by an art historian who studied the same problem (Mark, 1982). This question about the justification for the pinnacles on pier buttresses raises a much more fundamental issue, one that arose in the 19th century with the renewed cultural interest in gothic cathedrals.

The story begins with the gothic revival in the late 18th century – largely a literary movement famous for the section in Victor Hugo's Hunchback of Notre Dame where he describes the sad state of that great Paris cathedral and begins to make a case for restoration of these works. The architect Eugene Viollet-le-duc took up this task as head of the commission for ancient monuments and proceeded to write profusely on the engineering and architectural features of these structures. One example will illustrate the issue of cracking.

In the cathedral at Amiens there are main massive pier buttresses that carry roof loads as well as other loads from the interior. Viollet wanted to show that all main parts of Gothic form were essential to the structural design or the construction process and one set of examples he took was the small pinnacle atop each pier buttress. Were they useful or were they merely decoration? Viollet answered this with a resounding yes in favor of useful because as he explained it there are vertical forces on the pier and horizontal forces. These former ones, he claimed, served to compress the masonry and the masonry within the buttress on the foundation and therefore the weight of the pinnacle would keep the pier buttress from sliding or bending outward.

This reasonable sounding defense of the utility of the pinnacle was attacked by the architectural historian Pol Abraham who ridiculed Viollet's logic by showing first that the small stone weight was too small to have any significant influence on the immense buttress with its large forces. Second, he argued that even if the pinnacle were of a helpful weight it was clearly in the wrong place (at the outer edge of the buttress) where it would contribute to its outward bending instability. Clearly, said Abraham, the pinnacle was a decorative feature to improve the appearance of an otherwise dull flat upper terminus of the pier buttress. Abraham used many more examples to illustrate what he considered to be the general fallacy that Gothic designers based their overall forms on structural and constructional ideas. This controversy between the so-called rationalism of Viollet and the illusionism of Abraham became an important debate in the 20th century where some architects designed to express structural or constructional ideals while others believed that those engineering features were irrelevant to the visible expression of form. But most agreed that the Gothic form was beautiful so Abraham's argument was essential to an architecture that strove to be separated fully from any expression of engineering. Was Abraham correct?

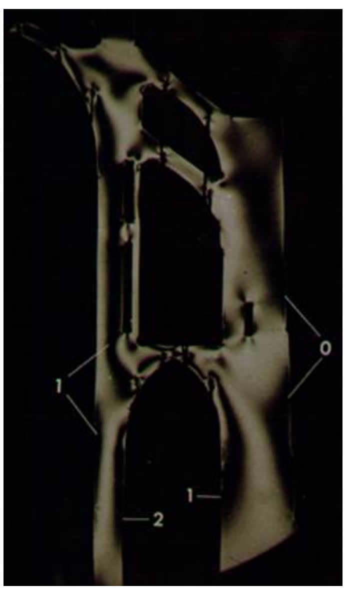

Figure 3. Photoelastic analysis of Amiens.

Robert Mark entered that debate with a series of examples for which the pinnacle is the simplest to describe. By means of photoelastic model analysis, he showed that without the pinnacle at Amiens there would have existed in one predominate place on the buttress a region of tension stress which could easily have led to cracking near the top outside edge (Mark, 1982) (Figure 3). He then reanalyzed the structure with the pinnacle on top and that tension disappeared. The strong supposition is that Gothic builders saw such tension because the structure is of course stone on stone and the interface could therefore easily open up. The pinnacles are therefore of just the right weight and in just the right location to eliminate that cracking. Once decided upon, as in much gothic architecture, the element was shaped elegantly so that the form is rational and the choice of detail was aesthetic. Here the response to cracking led to an elegant addition to the already striking exterior form of high Gothic structure.

4 THE PERIOD OF EARLY ADVANCES IN REINFORCED CONCRETE

A number of entrepreneurs began to design and build reinforced concrete structures before 1900 and major advances came soon thereafter. Probably the most widespread system of design-build was that pioneered by the French engineer, François Hennebique, one of whose most famous structures was the bridge over the Vienne River at Châtellerault in 1899. Engineers admired the lightness of its three arch spans but the more perceptive ones recognized that the arches exhibited cracking at both supports and at the crown. This cracking led one of Hennebique's employees in 1900 to propose an arch design with hinges built in at each support and at the crown. This three-hinged arch could expand or contract as the ambient temperature changed without cracking because the hinges allowed freedom of movement (Billington, 1976).

This young engineer, Robert Maillart (1872-1940), made the design for a single-span arch bridge over the Inn River at Zuoz in eastern Switzerland; it was completed the following year. Maillart used that opportunity to design a completely new form in concrete – the hollow box – in which arch, side walls, and deck were all built together in one monolithic form that was far stronger and substantially lighter than Hennebique's bridge and other concrete arch bridges of that time (Billington, 1976).

Hennebique's bridge cracking suggested to Maillart the three-hinged form but he was concerned that the increased flexibility owing to the hinges would make the structure too light and subject to higher stresses and more serious vibrations under traffic load. Maillart therefore, by overcoming the cracking problem, went on to overcome the extra flexibility through a greatly stiffened arch achieved by connecting it to walls and the roadway deck. This led him to his great innovation, the concrete hollow box – still a major form for bridge design in the 21st century.

But here Maillart was misled by his knowledge of classical forms, especially that of Roman arch bridge design that had been transferred to keep the Pantheon from dangerous arch bending. In their bridges the Romans had used circular forms to simplify construction by cutting the stones all to the same wedge shapes. They were good engineers and knew that the circular shape was wrong so they corrected for it by piling extra weight near the abutments (what we would call changing the pressure line to keep it inside the kern). This weight was normally rubble masonry and being loose required spandrel walls on either side of the arch. These containment walls reached from arch to deck and gave the visual impression of a haunched beam-arch that by the 19th century was an accepted aesthetic form for water crossings. Michelangelo's famous bridge over the Arno River at Florence is a fine example of such a bridge.

So Maillart designed the walls for his hollow box to extend all the way to the abutments even though the support hinges were placed in the arch well below the walls. The result was a set of cracks in the spandrel walls that arose from differential movements between the arch (wet from the river) and the deck (dry and hot from the sun of the Oberengadine) (Figure 4). The owners of the bridge called Maillart to the site several years later to explain the problem and determine its danger. Maillart realized that there was no danger of failure but rather of gradual deterioration through heavy weather – he recommended whitewashing it for protection. The bridge lasted well for 65 years; it was then rehabilitated and is in good shape today.

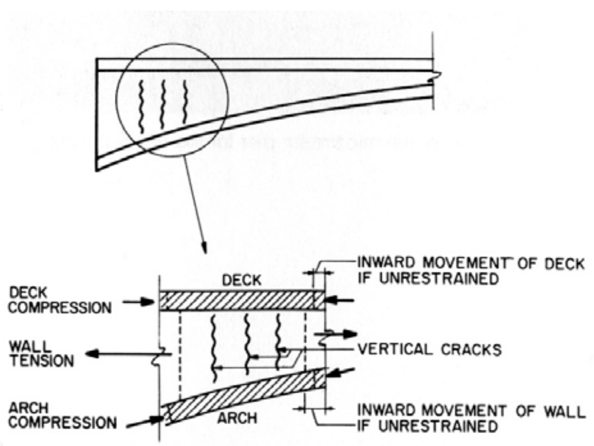

Figure 4. Zuoz Bridge and cracks.

But the cracks set Maillart thinking deeply about his form and he realized that the spandrel wall was unnecessary near the abutments so that in his next new project, the Tavanasa Bridge of 1905, he removed that part and produced a clear expression of the three-hinged form (Figure 5). This was the first example of a great concrete work of structural art; it was also efficient in using a minimum of material and economical in being built by Maillart himself as the least expensive in a design-build competition. The high art world of Switzerland was, however, hostile to this completely unprecedented shape and for 25 years Maillart could not complete a bridge in that form. He therefore turned to other bridge forms and once again cracking came to the rescue of creativity.

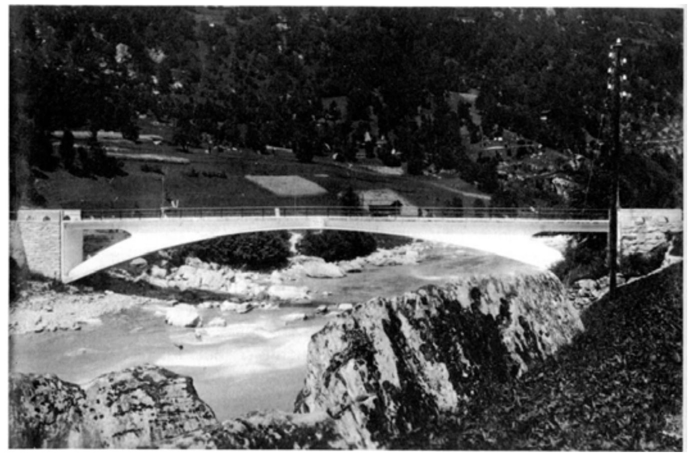

Figure 5. Tavanasa Bridge.

In 1910 the cantons of Aargau and Solothurn asked for design-build bids for a bridge over the Aare River near the town of Aarburg and three companies submitted bids of which Maillart was second lowest in price. Because of his strong reputation for high quality construction, Maillart gained the contract, designed a traditional arch and completed construction in 1912. A few years later the owners called him back to the site to explain cracks in the deck above the arch (Figure 6). This defect surprised Maillart because his design was thoroughly conventional – almost Roman in concept – where he designed the deck to carry loads to the columns which in turn transferred those loads to the arch which carries all the load to the abutments. There was no interaction; he designed each part to carry all its loads with no help from any other part.

As Maillart thought about this problem which, as at Zuoz, did not signal a danger of collapse, he began to realize that the location and extent of the cracks were expressive of a structural behavior that he had not anticipated and which reminded him of an idea presented in class almost 30 years earlier by his professor at the ETH, Wilhelm Ritter (Ritter, 1883).

The lesson was that a monolithic structure will act as a single unit even if the analysis imagines it to be individual elements acting separately as was the standard approach. He saw that when the arch deflected under traffic loads over half the span, the deck must also deflect that way and not, as he had assumed, as if it were deflected over the far shorter length between columns. The cracks illustrated that behavior clearly and this problem stimulated Maillart to invent his second major bridge form beginning with a small 1923 bridge over the Flienglibach. Here he used the parapet as a stiffener to carry the half load bending and as a consequence he could design the arch about one-third the thickness of the arch at Aarburg. This new idea found full expression two years later in the Valtschielbach Bridge (Figure 7). As with the 1905 Tavanasa, this 1925 bridge signaled a major new design using the potential of monolithic concrete and resulting from an earlier design that exhibited highly visible and extensive cracking. Neither of these two bridge innovations, however, reached the highest point of structural art that those cracking experiences promised. Maillart would achieve that point during the last decade of his life from 1930 to his death in 1940.

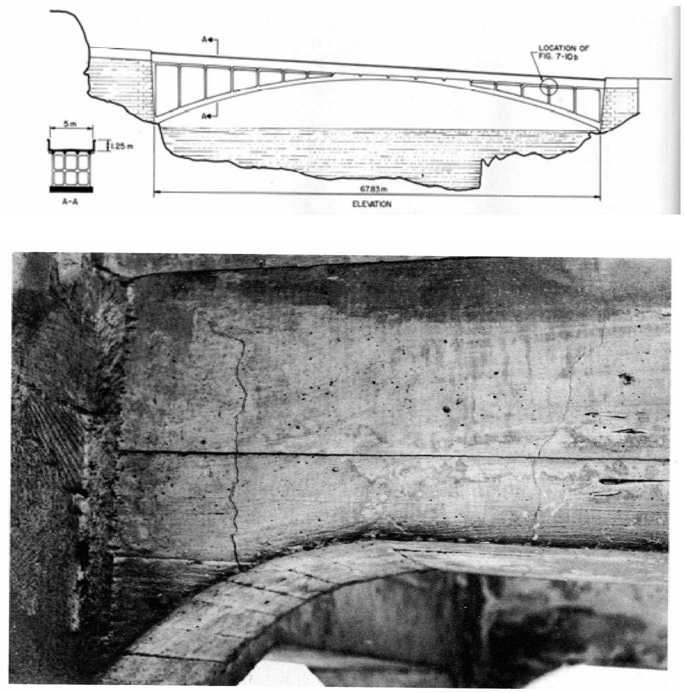

Figure 6. Aarburg Bridge and cracks.

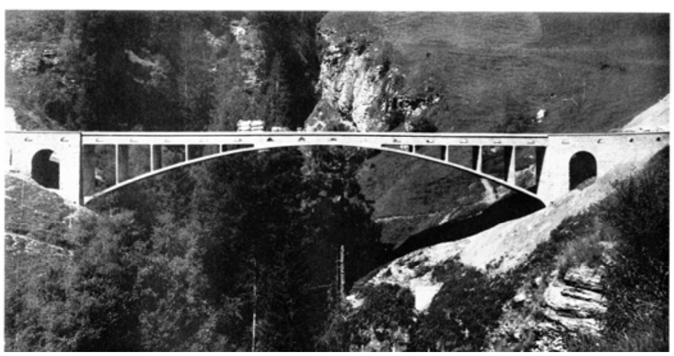

Figure 7. Valtschielbach Bridge.

5 PRESTRESSING AND CRACKLESS CONCRETE

In the meantime another more sweeping innovation appeared. While cracks can stimulate creativity it is also true that the possibility of completely eliminating cracks can inspire hopes for a new world of structural design. Such was the vision of a French engineer who first imagined such a world in the same year that Maillart first saw his cracked Zuoz Bridge. This Frenchman, Eugene Freyssinet (1879-1962), developed the idea, patented it and began using it only after the age of 50. Later he would express his vision that prestressed concrete held much more promise than just one more development because, as he wrote in 1949, "in itself the idea of prestressing is neither complicated nor mysterious; it is even remarkably simple, but it does belong to a universe unknown to classical structural materials and the difficulty for those first coming to the idea of prestressing is to adapt themselves to this new universe." Even Hennebique had not claimed so much for reinforced concrete, although its properties could have rightly been called unknown to the universe of stone, wood, and iron structures. Yet both Frenchmen proclaimed a new era in building based on the union of metal and concrete, and both sought what Maillart had called the lightness of metal and the permanence of stone (Billington, 1985).

Because this was a "new universe", Freyssinet claimed that "the fields of prestressed and reinforced concrete have no common frontier". Either a structure was fully prestressed or it was not prestressed concrete. Either the design was to be fully crack free or it was not part of the "new universe". His idea was revolutionary, it was stimulating, it had productive results, but it was wrong.

Nevertheless, in the United States it became the rule that prestressed concrete was distinctly separate from reinforced concrete and to this day almost no civil engineering undergraduate, while taking a course in concrete structures, has been exposed to prestressed concrete. In standard texts prestressing is usually relegated to a single separate chapter or left out entirely. There is no doubt that prestressing was a true revolution in structural engineering and it would lead eventually to beam bridge spans of 1000 feet and to the economical use, as Freyssinet predicted, of high strength steel and high strength concrete. But as a new universe of crack free forms it would be more a questionable idea than a sweeping change. I can illustrate an example of the dangers inherent in the early idea of crack free design by taking the concept which, although not strictly speaking prestressing, nevertheless shows the problem.

In the 1960s there began to be built large power plants, some for nuclear power but others using fossil fuel. One striking visual component of many such plants was the natural draft cooling tower reaching above 300 ft. in height and eventually over 500 ft. high. Originally these towers were designed quite simply for dead weight and wind load where the base stresses due to each counteracted (compression for dead load and tension on the windward side for wind load). Because they were made to balance, very little vertical reinforcing steel was used. As an example, if the dead weight gave a maximum of 2000 psi compression and the wind load (assumed here as 100 mph) gave a maximum of 2000 psi tension, the design result would be zero stress at one point and some expression elsewhere around the circumference of the thin shell tower. What happened to a set of such towers in 1965 was that there occurred a wind higher than the design by only about 12% (112 mph). Since the pressure is proportional to velocity squared that meant the maximum tension increased by about 25% to roughly 2500 psi, leaving a net tension of 500 psi and hence cracking. Three towers failed and the primary lesson was that there needed to be an ultimate load analysis as well as the correct working load analysis that was used (Central Electricity Generating Board, 1966) (Figure 8).

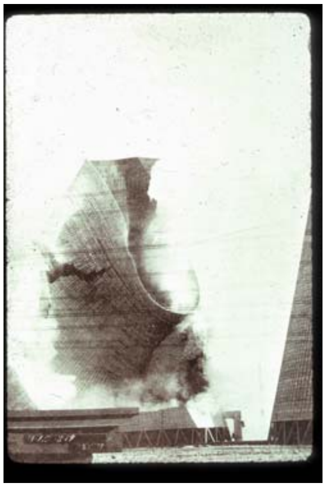

Figure 8. Ferrybridge cooling tower failure.

Thus the concept of crack free design did not initially include a concern for overloads. Freyssinet was far too good an engineer to have made a mistake like that. But his enthusiasm for prestressing did require, for the profession as a whole, the additional emphasis on the potential for a cracked state and subsequently for the assurance of appropriate reinforcing still to prevent danger.

Fortunately three engineers almost immediately after World War II, when Freyssinet's ideas began to receive serious attention, spoke out strongly in favor of a more balanced view, one which still recognized the extraordinary potential for prestressing but one which recognized the great significance of recognizing cracking as an integral part of design. This recognition led to a new concept for prestressing that would bring in a new era in understanding concrete structural engineering - not the new universe postulated by Freyssinet, but still a new universe that was inclusive rather than exclusive.

6 STRUCTURAL CONCRETE AND THE CENTRALITY OF CRACKING

The three pioneering structural engineers who took issue with Freyssinet saw that prestressing was really a new idea that should be seen as improving reinforced concrete structures rather than supplanting them. The first was Paul Abeles, an Austrian who fled from fascism and brought his ideas to Great Britain. His idea which he named partial prestressing was to provide enough prestressing to control cracking in reinforced beams rather than to completely remove it. His designs aimed first at railway beams where the high live load caused the greatest tensile stresses. If these were to be fully counteracted by prestressing there would remain, with only dead load, large stresses (both compression and tension) due to the prestressing and also the possibility of large upward displacements. Abeles argued that since reinforced concrete practice permitted cracking, why not allow some and use reinforcing steel to control cracking and carry live load. The prestressing would carry dead load so that most of the time – when the heaviest trains were not running over the elements – there would be no cracking or, more properly put, the cracks due to live load would be closed (Abeles, 1962).

Abeles found a sympathetic colleague in the second major figure of the post war era, the Belgium professor of structures Gustave Magnel (1889-1955). Magnel was one of the two greatest teachers of structures that I know about during this post war time and he carried out numerous tests in his well equipped laboratory at the University of Ghent. His tests on Abeles' designs materially helped the Austrian make his point about partial prestressing but even more importantly Magnel had the background and depth of understanding that allowed him to openly dispute Freyssinet (Magnel, 1954).

An ally of Magnel's in combating the extreme position of Freyssinet was the Swiss professor, Pierre Lardy (1903-1958). Like Magnel, Lardy produced (with his predecessor Max Ritter) a pioneering text on prestressed concrete in the 1940s and like Magnel, Lardy was a superlative teacher who taught prestressed concrete to his students in the late 1940s. Lardy's two most famous students both took up the issue of cracking but from different perspectives (Billington, 2003). Christian Menn (b1927), the most gifted bridge designer of the last half century, quickly followed the ideas that Magnel and Lardy had emphasized that prestressing and reinforcing should not be separated. In Menn's bridges he often used prestressing to counteract dead loads and sometimes part of the live load and then employed reinforcing steel to carry the remaining load.

One clear example is the transverse reinforcement in the hollow box deck for the 1974 Felsenau Bridge (Figure 9). Here the wide cantilever overhangs are prestressed for dead load and reinforcing steel added to carry the live (traffic) loads. This allowed Menn to have unusually long cantilevers which provided a substantial shadow on the web of the box and contributed to the light appearance of the haunched main spans (the longest in Switzerland at the time). Had he tried to follow Freyssinet's crack free universe the cantilevers would surely have been overstressed when no live load was present and probably deflected upward as well. Menn thus achieved the high goal of the structural artist by allowing for cracks and creating thereby a more elegant design (Billington, 2003).

Figure 9. Felsenau Bridge and wide overhanging wings.

Lardy's other most famous student, Heinz Isler (b1926), actually realized Freyssinet's goal of a new universe but without the prestressing that the French engineer believed essential. Isler's new universe is truly a revolution in concrete design that the profession as a whole has only barely recognized. Isler achieves crack free roof spans in reinforced concrete entirely by creating unprecedented shapes that avoid almost entirely any tension stresses and hence any cracking. In this way Isler's thin shell concrete roofs, with spans sometimes above 150 ft., are entirely waterproof and are built with no roofing or other water proofing materials (Figure 10). They are bare concrete usually only three inches thick and created by his hanging membrane reversed process. In this process, Isler invents a form by suspending a cloth between the desired number and location of supports. He then pours on the cloth a fluid plastic which causes the cloth to assume a shape dictated solely by gravity. When the plastic hardens, Isler overturns the model (of the order of three feet in span) and measures the ordinates precisely so that the full scale structures will be built of the same form (Billington, 2003).

These shells are designed so that the model supports and the real structural supports are usually at ground level and then, because the shells are curved, there will be both vertical and horizontal reactions needed for stability. Isler ties the supports together by prestressing tendons normally below grade. The secret of Isler's crackless concrete, therefore, is not direct prestressing but rather the creation of a new form, largely loaded by gravity, that will by its shape avoid cracks and lead to a new vision for concrete.

All of these events have led to a new designation, structural concrete, which is a material that makes no exclusive claims for either prestressing or reinforcement but rather considers them each as part of the designer's education and practice. Two major figures in concrete structural engineering of the 20th century are credited with advancing this term: John Breen, a distinguished professor at the University of Texas at Austin and Jőrg Schlaich, both a professor at Stuttgart but also head of one of the most creative design firms.

Figure 10. Sicli Building with no waterproofing.

7 CONCLUSION

This paper has sought to illustrate, through specific design examples, the way in which the contemplation of concrete cracking has led to new ideas and new designs. In a more general way, this brief study also seeks to emphasize the centrality of historical cases to the education of students as well as practitioners. Isolated or disconnected historical case studies are usually of much less significance than a set of such cases that are connected by a central idea. That is what makes history both important and of interest in education. This present sketch attempts to develop the idea of cracking as an important part of concrete studies not only as scientific analysis but also as design insight.

ACKNOWLEDGEMENTS

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