C H A P T E R 2

THOMAS TELFORD AND THE NEW ART FORM

We saw in chapter 1 that there are two main periods of structural art. The first one followed on the heels of the Industrial Revolution, beginning in the late eighteenth century and spreading throughout the world for about the next one hundred years. The second period began in the late nineteenth century and continues to this day. The primary distinctions lie in the materials and the forms. In the first period, the material is iron and the forms tend to be visually complex; in the second, the materials are steel and concrete, and the forms tend to be visually simpler.

The Eiffel Tower and Brooklyn Bridge are structures that stand between the two periods. They were not technological breakthroughs but, as the last structural designs of the two most famous bridge builders of the nineteenth century, they were climaxes as well as promises. The primary motivation of each was to span unprecedented distances with iron, the material of the Industrial Revolution. It was because Eif-
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feh and Roebling created new forms in iron, on a new scale, and in permanent locations, that their works characterize the modern world. Although, perhaps obvious, it is nonetheless crucial that such structures could not have appeared before the Industrial Revolution, because industrialized iron did not then exist. The tower and the bridge, therefore, were not in the 1880s just portents of the future; they were also culminations of the past. The material of Eiffel’s tower was iron, not steel, so in this respect it belongs to the first period, but its form set the direction for new forms in steel. Conversely, Roebling’s bridge was the first major one to use steel rope for its cables, but the vertical suspenders and diagonal stays of its form looked back to the more complex forms of the past. The two structures will be discussed further in chapters 4 to 6, particularly how they follow from the developments considered here, lead to the developments taken up in the second part of this book, and exemplify the ideals of structural art which are our focus throughout.

The Second Iron Age

In looking at the first period, the major question we must ask is what happened during the Industrial Revolution to make possible the new art form of structure. The central material fact of the Industrial Revolution is iron. The new methods of producing that ancient material preceded and were essential to the most famous technological development of eighteenth-century Britain: the steam engine. And, without these new methods, and hence cheap and plentiful iron, developments in industry could not have been sufficient to merit the term “revolution.” The new methods involved replacing charcoal with coke in the smelting process. Using the energy powerhouse of coal in place of the far weaker store in wood, the iron founders of the West Midlands could begin to supply iron for machines and structures previously made of wood. Thus coal replaced wood in the process of iron making and in turn iron replaced wood for the products. In both cases, a far denser and stronger material supplanted the softer organic substance that had held together the technology of earlier civilizations. A nonrenewable resource replaced a renewable one; that is the primary ecological fact of the Industrial Revolution. Society thus began to mine its geological capital rather than fell its agricultural income. At the same time, the immediate power that was available increased enormously and centralized production became more and more economical. In this way, by the late eighteenth century, the development of industrialized iron came to define the course of technology and of society as a whole.

The most enduring symbol of the eighteenth-century rise in iron production is Iron Bridge (figure 2.1), built in 1779 by Abraham Darby III from cast-iron pieces. When it proved to be the only bridge in the
Severn River region to survive the disastrous 1795 Severn River flood, Thomas Telford, the founding president of the world's first civil engineering society, turned from masonry to metal and began to create the first series of iron bridges that demonstrated unequivocally the personal style of a structural artist. It was clear to Telford that Iron Bridge had survived that flood undamaged precisely because of the key property of iron, its high strength. Early cast iron was about five times as strong as wood and hence required one-fifth the amount of material to carry the same load. This drastic reduction in quantity of material allowed the design to let more water flow past the bridge during a flood. Masonry bridges acted as dams, building up water pressure that easily destroyed stone works. Wooden bridges, as well, had a damming effect and moreover were susceptible to breaks in joints and to flotation.

The visual lightness and the strength displayed by Iron Bridge stimulated Telford and others around the turn of the century to think about the new material and new forms. At first, of course, they still thought in terms of stone or wood structures, and many designers tried merely to put the new material into the old forms. Iron Bridge itself has the semicircular form typical of stone arches and its joined pieces are reminiscent of timberwork. But for Telford the new material also provoked a different type of thinking. More than any contemporary, Telford saw the possibilities for a new visual world of iron, because he focused always on objects rather than theories, on economy of field construction rather than the business of designing structures, and on large-scale, public works rather than private architecture for the aristocracy.

Thomas Telford and Bridge Art

Telford was born in Glendinning, Scotland, in 1757. He began his career as a mason, and in 1778 helped build a three-span masonry arch bridge at Langholm. In 1782, he left Scotland for London to find a larger scope for his energies. In London, he worked as a draftsman in an architect's office, and between 1784 and 1787 he did alterations on the Shrewsbury Castle in Shropshire. Along with this architectural work, as a county surveyor from 1787 he designed his first bridge, three stone arch spans built at Montford and completed in 1792. By that time his talent for large-scale works began to be recognized; and, when the directors of the proposed Ellesmere Canal offered him the chance to carry out this immense project, Telford accepted the position, writing later:

Feeling in myself a stronger disposition for executing works of importance and magnitude than for details of house architecture I did not hesitate to accept their offer, and from that time directed my attention solely to Civil Engineering.

This reflection might be called the first self-conscious statement of the new engineering, fully disconnected from architecture and yet intimately related to the Industrial Revolution. Telford's decision led directly to the most impressive metal monument of eighteenth-century design still standing today: the aqueduct at Llangollen known as Pont-y-Cysylte, completed in 1805 and functioning today with the original cast iron still fully intact.

From 1795 on, Telford worked with cast-iron structures, but it was in the Bonar Bridge design in 1810 that his ideas matured to the point where a new form emerged. For this bridge over the Dornoch Firth in Scotland, Telford proposed a 150-foot-span cast-iron arch. He chose this wide span rather than the normal two-span masonry solution of earlier times in part because of flood and ice dangers. But more important were his design criteria: "to improve the principles of constructing iron bridges, also their external appearance ... [and] to save a very considerable portion of iron and consequently weight." Telford thus stated the central ideas of this new tradition—efficiency in materials, economy for construction, and appearance of the final form—and they have remained those of all structural artists ever since.

Telford's iron arch bridges were not the only such works at this time nor were they the longest spanning ones. The 1796 Sunderland Bridge spanned 236 feet, and John Rennie—Telford's only rival as Britain's finest bridge designer of the period—designed the 1819 Southwark Bridge with a central cast-iron arch span of 240 feet. But what sets Telford apart is his distinct personal style; his iron arches are more visually attractive than those of his contemporaries, and they are also
The Craigellachie Bridge over the River Spey, Elgin, Scotland. 1814, by Thomas Telford. This flat 160-foot-span, cast-iron arch is the oldest surviving bridge of a type representing the first modern metal bridge forms. The arch, made of trussed elements having a constant depth, is fully continuous between abutments.

FIGURE 2.2

technically superior. A recent compilation of cast-iron bridges built between 1779 and 1871 lists the bridges in order of their technical quality. Of the top nine listed, eight are by Telford. Of those eight, five are still standing today.

The oldest surviving bridge of the Bonar type is the 1814 Craigellachie Bridge (figure 2.2). Its arch is a flat circular profile of constant depth made up of two curved pieces connected by X-braces and radial struts. The thin roadway has a slight vertical curve and is joined to the arch by thin diagonal members whose general direction is radial. The whole form is light and open, the iron structure is the visible form, and the arch is made of standard pieces throughout its curved length. Although some of the visual elements derive from wooden bridges, the overall design as first conceived by Telford in 1810 represents a new form and one appropriate to cast iron.

There is no doubt as to Telford’s aesthetic intention. He wrote with feeling about his Scottish landscape and about the beautiful Llan-

gollen setting for the Welsh aqueduct. He was closely enough connected to the architects of his day to absorb their love of the picturesque and to sense the significance of setting to a structural form. But he was the first civil engineer consciously to move away from the old canons of architectural taste. He did not write about the old architectural ideas of proportion, symmetry, and rhythm, but rather about the new engineering problems of construction, weight, and foundations. He was thinking all the time about appearance and landscape and form but, for Telford, the possibility for beauty must come internally from what the technical and economic constraints suggest, rather than externally from the images and formulations refined over centuries in the architecture of masonry.

Telford and the Limits of Structure

Cast iron liberated the imagination of Telford and others. It literally founded the modern engineering profession by forcing a group of designers to think deeply about structure at a new scale. Telford was first stimulated to think about very long-span bridges when in 1799 the Houses of Parliament appointed a select committee to investigate numerous proposals for the much-needed new London Bridge. It had been proposed to span the Thames in one span to allow shipping to pass beneath. The lightness and the strength of cast iron suggested the solution. Of the many proposals, Thomas Telford’s 1800 design for a cast-iron arch of 600 feet in span impressed the committee the most. There followed an extensive feasibility investigation which involved nearly every major user of cast iron in the emerging profession of engineering. Those consulted included various university professors, James Watt, John Wilkinson, the famous iron founder, and John Rennie. Although the consensus was that Telford’s immense and elegant design could be built, Parliament never acted on it. This design was the earliest forerunner of Eiffel’s tower and Roebling’s bridge, and it foreshadowed the drama of each. Its proposed lace work of iron and great height would have dominated London visually as Eiffel’s work was to dominate
Paris nearly a century later; and the undoubted spectacle of seeing a city while crossing a bridge anticipated the visual excitement of Roebling’s central elevated walkway to Brooklyn. It was, however, just this height, which had so stimulated Telford’s imagination, that led to the great cost of the bridge approaches and also, presumably, to the parliamentary neglect. Entrusted with the eventual construction of both the Waterloo (1817) and London (1831) bridges, John Rennie fell back on older Parisian examples of multiarch stone works and thus reinforced the prevailing attitude that masonry was the proper city material. Needless to say, such stone posturing did not appeal to Telford.

Despite its importance, Telford’s London bridge design was not truly modern in form. Influenced, perhaps, by the Sunderland design of 1796 (itself stimulated by ideas from Thomas Paine), Telford imagined a series of parallel arched elements, somewhat similar to the three paralleled arches in Iron Bridge, only very flat. Although his bold design stimulated others to propose long-span arches, Telford himself departed from this Iron Bridge-type precedent and developed the different form of the Bonar type in 1810. In his autobiography, Telford never mentioned the Thames bridge design, nor was any illustration included in his Atlas of Works. He did briefly refer to it in his 1812 “Bridge” article but gave no drawing of it, preferring instead to emphasize his Bonar Bridge and his 1811 proposal for a Bonar-type 500-foot arch over the Menai Straits.

After 1800, Telford turned his energies to the outlying regions, where he could proceed to develop new forms in response to the new industrial needs. In 1803 he became engineer to the commissioner for roads and bridges in the highlands of Scotland. It was in this position that—with the Bonar and the Craigellachie—he began to design what we have characterized as the first set of iron bridges to show the integration of technological soundness and handsome form. From the highlands of Scotland, Telford would move to the hills of Wales and to the outer limits of structure, not with the arch but with the cable, not with cast iron but with wrought iron.

The second iron age began in the foundry and was first made visible by arches of cast pieces designed and assembled in ways related to stone arches. Wrought iron, on the other hand, came from the forge, and first found major structural use in the chains of early-nineteenth-century suspension bridges. Cast iron, like stone, is far better in compression (squeezing together) than in tension (pulling apart); it is more impervious to weather than is wrought iron. Therefore, the obvious replacement for stone in arch bridges was cast iron, and the obvious material for the cables in the new suspension bridges was wrought iron.

The first three decades of the new century saw the suspension bridge come from the rope-hung exotica of South America and China to the heart of the Industrial Revolution. Britain led the way. The single greatest work of this period was Telford’s 580-foot-span bridge, completed in 1826 over the Menai Straits in northwest Wales (figure 2.3). His was the first British bridge to be indisputably the longest span in the world. It is the most important work in Telford’s remarkable career, and it stands today as a symbol of the great aspirations of pre-Victorian Britain. Its design and its subsequent history reflect both the promise and the perils of an industrial world.

The bridge was over the most difficult section of the Holyhead Road connecting London to the Dublin ferry in Holyhead, on the is-
land of Anglesey. The overall project for an improved connection between London and Dublin, spurred by the 1800 union of Ireland with Britain, was given to Telford in 1810, and the bridge design was accepted by Parliament in 1817. Nine years later, on January 30, 1826, the London mail coach galloped across the first bridge to span directly over an open reach of ocean.11

But the bridge was doing some galloping of its own. Telford’s resident engineer, W. A. Provis, had noted undulations from gusting wind just before the bridge opened.12 Telford then added transverse bracing, which cut down the movement. No significant motion occurred until ten years later, two years after Telford’s death. In January 1836, the bridgekeeper reported large oscillations to Provis, who recommended a longitudinal stiffening of the roadway. Sadly, no action resulted, and in 1839 a gale tore part of the roadway loose. This severe damage to both carriageways was rapidly repaired and Provis then designed a stiffening of the roadway that lasted over half a century. A steel deck replaced the original roadway in 1893 and the entire bridge span was rehabilitated in 1940.

Telford’s writings in the 1820s and Provis’s field observations show a clear awareness of how horizontal wind can cause extensive vertical motion in a suspension bridge. Telford realized that a longitudinal stiffening of the deck would reduce that danger, but he felt unjustified in adding that costly provision until such time as it might become unavoidable. Had he been alive in 1836, it seems plausible that the bridgekeeper’s report would have led Telford to make those changes, his great prestige insuring their implementation. It is thus possible that no severe damage would ever have arisen and that Menai could have been regarded as a full success.

As we shall see, great structural artists have always learned from the full-scale performance of their own works and the works of others. Roebling changed his Niagara Falls bridge design while the bridge was under construction, after he heard of the failure of the Wheeling Bridge in 1854. The birth of prestressing, the most revolutionary structural idea of the twentieth century, can be traced back directly to Eugène Freyssinet’s 1910 bridge at Le Veudre, which after completion would have collapsed into the Allier River had the designer not applied emergency jacking by night to save it. Othmar Ammann, designer of the great New York bridges from the George Washington to Verrazano, wrote in 1953 that “the Tacoma Narrows bridge failure has given us invaluable information. . . . It has shown [that] every new structure which projects into new fields of magnitude involves new problems for the solution of which neither theory nor practical experience furnish an adequate guide. It is then that we must rely largely on judgement and if, as a result, errors or failures occur, we must accept them as a price for human progress.”13

All of these structural artists worked at the limits of structure. These limits are just what stimulate imagination and are a primary basis for the aesthetics of this new art form. This was certainly true in Telford’s case, and with undeniable results. Of all the suspension bridges completed before Telford’s death, none were built as well as Telford’s and none had such a strong influence aesthetically on subsequent design. In addition to Menai, Telford designed the 380-foot-span Conway suspension bridge also completed in 1826 and standing in good condition today.

Art and Politics

Menai is the first major work of structural art visually to symbolize, in its thinness, the lightness of the new engineering and the demands of the new politics. The bridge was contemporaneous with the Reform Bill of 1832, the primary effect of which was to give representation to industrial cities such as Birmingham, Manchester, Leeds, and Sheffield. Politics was being directly influenced by the Industrial Revolution. Spreading the franchise more widely went together with spreading materials more thinly. Both actions called forth new forms.

In politics as in structure the risky idea of new forms proved exciting to the new designers. No one better exemplified the connection between the two spheres than Thomas Paine. His two primary interests were structure and politics; he termed The Rights of Man his “political bridge.” Paine’s designs for iron bridges had considerable short-term influence in both Britain and America, where his elegant models encouraged some designers to think of long spans with thin metal sec-
Telford's Aesthetic

Telford took a strong stand for the independence of engineering, both from the visual maxims of eighteenth-century architecture and from the mathematical ideals of eighteenth-century science. Ornamental facades and scientific abstractions, coming from the elite academies rather than from the provincial building sites, violated his instinctive sense of form. One of his writings shows Telford's aesthetic thinking, unique in Telford's own time but closely similar to writings by later structural artists, the section on "Bridge" for the Edinburgh Encyclopedia was written in 1812. In 1813, several of his bridge reports were printed in the House of Commons Reports. 16

In the "Bridge" article, Telford critically reviewed previous iron arch bridges: Iron Bridge, Buildwas, Sunderland, the 1800 Boston Bridge of John Rennie, the 1805 bridge at Bristol, and his own 1810 Bonar Bridge design. He began his discussion by noting that iron bridges were "unquestionably a late invention of British artists," and that the main problem with Iron Bridge was that "more skill than that of the mere ironmaster was required." His use of the word "artist" is pre-romantic and hence cannot have the same meaning as we would give it today. But, for Telford, the word does mean someone dedicated to both skill and beauty. His article moves effortlessly back and forth between technical discussion of connections and member sizes and criticism of appearance; he sees no separation between use and beauty. This 1812 article is the first treatise by an engineer on structural art.

Telford described how the iron circles between the ribs and the deck both in Iron Bridge at Coalbrookdale and at Sunderland are the wrong form and are wasteful of material. The two higher circular ribs at Coalbrookdale do not carry the load well and they have "a mutilated appearance." In Rennie's Boston bridge, which had cracked badly when built, Telford observed that "the ribs, in springing from the perpendicular faces of the masonry of the abutment, have also a crippled appearance." He went on to observe that at Bristol "the supporting pillars [between road and arch] are still placed perpendicularly [vertically],... which, as the arch has more curvature, has still a worse effect than at Boston."

All of these aesthetic objections Telford had sought to overcome in his Bonar bridge design. This design involves a single arch span, supported by a masonry face cut perpendicular to the arch slope, and in the spandrels, instead of circles or upright pillars, "lozenge, or rather triangular forms are introduced...[to keep] the points of pressure in the direction of the radius...this disposition of the iron work, especially in the spandrels, also greatly improves the general appearance." 17 For him it possessed the basic virtue of being a technical and an aesthetic improvement, and that integration is the central motive of all structural artists.

As we have seen, Telford separated engineering from architecture as early as 1793, but nevertheless always retained an interest in the latter. In an 1813 article in the Edinburgh Encyclopedia on "Civil architecture," he emphasized that the primary visual purpose of architecture was to express its load-carrying function. 18 For Telford, it was the laws of nature and the needs of society that gave stimulus to form, not pre-
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conceived aesthetic rules. Yet many writers on aesthetics believed then and believe now that forms arising from laws of natural science, or from social necessity, cannot be art. "We are in the presence of a work of art only when it has no preponderent instrumental use, and when its technical and rational foundations are not preeminent." This mid-twentieth-century view of art historian George Kubler—a view excluding useful objects and rationally based forms—has its origin in the philosophy of Immanuel Kant. As Kubler puts it, "Kant . . . said . . . that the necessary cannot be judged beautiful, but only right or consistent. In short, a work of art is as useless as a tool is useful."19

Kubler took an eighteenth-century viewpoint that separated fine and useful arts and that defined the process of artistic production, in Kant's words, as "purposeness without a purpose." The artist must be both original and disciplined (have purposeness) but he must not merely follow rules from society or laws of nature. Furthermore, the goal of the artist, in Kant's view, is the communication of aesthetic ideas through sensible forms, "and these aesthetic ideas are fictional, requiring works of art to be things which are 'in their own right, for their own sake.'"20 Art is for the sake of art. Kant's thinking was necessarily uninfluenced by the Industrial Revolution. It was easy for him to see art (in our sense of the word) as fine art and useful art as merely craft.

Telford, and succeeding structural artists, recognized intuitively that the new materials changed radically the old separation between the fine and useful arts (art and craft). Structure would begin, with Telford, to liberate the imagination and take its place with the other plastic or visual arts of painting, sculpture, and architecture. It would begin to communicate aesthetic ideas and to show how an aesthetically designed object can at the same time be a useful work. Structure would, after the introduction of cast iron, show how preeminent rational foundations could communicate the artist's aesthetic ideas while actually enhancing instrumental use of safely conveying people across wild ravines.21

The major artistic results from the Industrial Revolution were structures which expressed the aesthetic idea that the constraints of society—uses—and the constraints of nature—rational foundations—were the proper stimuli to imaginative form in a world forever changed. Today many would dispute this idea, arguing that in fact the constraints of society and nature must be transcended if art is to arise. The genius must be freed from ordinary rules, allowed to express himself through an unfettered imagination and an "artistic" life. Telford was not such a genius and his works, nearly all of which still serve their intended purpose, certainly do not reflect uselessness. Moreover, Telford was the most technically sound of the pioneering designers as well as the one who gave most weight to aesthetics. He is the first modern engineer to show that a concern for aesthetics does not compromise technical quality but rather can improve it. We have already argued that the aesthetic motivation in a structural artist seems in fact to stimulate efficient designs. It remains for us to explore how it can be that such designs can be both art and technology.

The two usual objections to the idea that technology can be art might be rephrased as questions. First, even if beautiful, are such designs merely the result of the meticulous application of science, dictated by their rational foundations, and devoid of any personality? Second, do not the pressures for economy, society's overriding constraint, make the expression of aesthetic ideas impossible, and is not the form merely a result of a drive for maximum profit to both the owner and the builder? What can an artistic designer hope to express of his imaginative and emotional longings when burdened by such considerations? These two questions can properly be answered only by exploring the sense in which a structural artist is constrained by scientific laws and social patterns. Again Telford provides us with the beginnings of an answer. The second question is simply an example of the general belief that design always converges to the most economical solution, economy being the society's quantitative measure. We shall take the question up in chapter 6.

Science and Engineering

The first of the two questions brings us back to the problem of whether technology is applied science. Does technological innovation follow directly from basic scientific discovery? As already indicated, we can derive some insights from Telford, his designs, and his writings.
Telford had little use for the science of his day, was untrained in mathematical formulations, and made few if any calculations for his designs. He was reputed to have no knowledge even of geometry, let alone the calculus invented in the seventeenth century by Newton and Leibnitz. It seems incredible today that without any mathematical analysis someone would seriously guarantee a 600-foot-span arch, over two and one-half times the span of any previous European bridge. Even more remarkable is the fine performance of his numerous extant iron bridges whose forms did not come from mathematical analyses. When saying that science had little influence on Telford, I mean two distinct ideas: first, that discoveries of nature’s laws by people like Galileo and Newton did not play any role in Telford’s designing; and, second, that Telford did not use in his design work the mathematical formulations devised by such researchers. Thus, science here means new discoveries and new methodologies developed independently of design imperatives. On the other hand, Telford directed innumerable tests on structural elements which he designed, and he also carefully observed the behavior of structures in service.

The clearest statement of Telford’s ideas on science appears, perhaps, in the second part of the three-part “Bridge” article in the 1814 *Edinburgh Encyclopedia*. This second part, entitled “Theory of Bridges,” was not actually written by Telford but at his request by Alexander Nimmo (1783–1832), one of his Scottish protégés. The ideas it expresses are fully consonant with Telford’s own. Telford had met Nimmo when the latter was rector of an academy in Inverness. Telford hired him to work on the Highland roads and in 1809 recommended him for a government appointment as an engineer in Ireland. There Nimmo designed a series of fine stone bridges which, according to Ruddock, are the equal of any of the French designs of the previous century. Nimmo was fully conversant in the science and mathematics of structural theory and had wide practical experience. His writing reflects this background but is enlivened by a firm belief that mathematical theory does little for the practical designer.

Nimmo’s article begins with Newton by implying that even Britain’s most eminent scientist had had little if any positive influence on engineering. Nimmo concides that “it was only [after] Newton had opened the path of true mechanical science, that . . . arches attracted the attention of mathematicians.” But, he continues, “we are much inclined to doubt whether the greater part of their speculations have been of any value to the practical bridge builder.” Near the end of the article he discusses the errors in Newton’s speculation on the flow of water around a bridge pier. In between these references to the great scientist, Nimmo simultaneously presents an essentially correct exposition of the principles of bridge design and conducts a polemic against the idea that scientific research has aided the practicing designer. He argues that the calculus is needless, that theoretical analyses impede design ideas, and that high precision in calculation is worthless.

Throughout the article Nimmo discusses proper form, which for him usually involves thinner structures. Thus the rejection of scientific theory goes together with a recommendation for design efficiency. Nimmo does give an arch theory, but one that is both computationally simple and visually oriented. It is based upon ideas empirically known to the Romans and used extensively by Telford and his generation. These ideas did not, therefore, come from the scientific revolution. Rather, as Nimmo is at pains to show, those eighteenth-century scientific refinements were more of a distraction than an inspiration to designers. He notes, for example, that the overemphasis on refining the mathematical form of an arch profile (parabola, catenary, circle, etc.) led analysts to neglect the importance of the foundations. “If the deductions of the theory were to be followed . . . they may lead . . . to the proposing of weakness instead of strength, and craziness instead of stability . . . . Give the modern engineer only a sure foundation, he will raise a structure as durable as the materials of which it is composed.”

The scientific studies have “led to no one useful practical result” because they have necessarily been constricted to the arch profile—which can be treated mathematically—and, in the meantime, “as to the thickness of archstones, side walls, and piers, the horizontal section or ground plan of the bridge, the manner of filling up its haunches, of forming the joints, of connecting it with the abutments, wing walls, etc., we are still left in the dark.” Scientific theory constricts vision and leaves out most of the practical problems. All structural artists since Telford have argued this thesis and its corollary that the simplification of analyses liberates the imagination.

It would be wrong to assume that Telford’s distrust of scientific studies led him to avoid all insights offered by mathematics. For the Menai Bridge, he carefully considered the opinion of Davies Gilbert
that the sag of the chains be increased from 34 feet (Telford's original design) to 50 feet (based on Gilbert's calculations). Gilbert, later to become president of the Royal Society, was a Holyhead Road commissioner. When Telford had presented his plans in 1820, Gilbert thought the chains too flat and set about to develop a mathematical theory which he later published in 1826. In the final design Telford did increase the sag, although only to 43 feet, and he gave credit to Gilbert for having influenced his design. Thus the scientific study followed the design and did not stimulate ideas on form, but it did influence the final detailed work. In other words, it was Telford's engineering design that stimulated Gilbert's scientific research. Art proceeded science in the development of engineering structure.

A recent study of Telford's highland roads and bridges concluded that "the whole enterprise shows Telford's great virtue as an engineer, his concern for economy, not in the short run, but in the long term. ... Functional but transcending merely functional, the bridges epitomize the grandeur of Telford's conception ... [and] for Craigellachie we can adopt [the poet] Robert Southey's quotation about Bonar Bridge, 'As I went along the road by the side of the water I could see no bridge; at last I came in sight of something like a spider's web in the air—if this be it, thought I, it will never do! But presently I came upon it, and oh, it is the finest thing that ever was made by God or Man!'"

This response to the "grandeur of Telford's conception" presages similar reactions to Brooklyn Bridge, the Eiffel Tower, and all other masterpieces of structural art. Telford had begun the new tradition with roadway bridges and canal aqueducts; the following generation of structural artists would continue it for the next major result of the new iron age: the railroad.

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**CHAPTER 3**

**BRUNEL, STEPHENSON, AND RAILWAY FORMS**

The Problem of Form

If iron was the maker of the Industrial Revolution, the iron horse was its mover. Darby's material and Watt's machine combined to accelerate wildly the pace of industrialization and urbanization in the twenty-five years between the completion of Telford's Menai Bridge and the 1851 opening of the Crystal Palace. Two British engineers, Robert Stephenson (1803–1859) and J. K. Brunel (1806–1859), dominated this period as Telford and Rennie had done the previous one.

Iron structure had moved out of the narrow confines of arch bridges and into a broader realm which included factories, public buildings, ships, and, above all, everything associated with railroads. As the centerpiece of the Great Exhibition, the Crystal Palace dramatized along its 1,848-foot length the visual power of huge open spaces framed with