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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 epitomise 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” prefigures 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.

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 I. 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
light, standardized, and prefabricated iron pieces. The structure and the form seemed one; the traditional “architecture” was relegated to exterior trimming. Significantly, the designer was a gardener, not an architect.

But such a building was an anomaly in nineteenth-century Britain. Even in industrial Manchester all the important buildings were of stone. An illustrated plan of the city in 1857 was surrounded by engravings of fifty-one civic, religious, and commercial buildings, all but one of which have facades of stone, and none of which shows the possibilities for new building forms with exposed structure.¹

While Manchester and other cities were building in stone from the wealth made possible by iron, engineers designed a bewildering array of structures to accommodate the railroads. The leaders, Stephenson and Brunel, were both artists in iron structure but they were caught up in the frenzy of the railroad to such an extent that neither would stop long enough to reflect deeply on structural form. Whereas Telford had worked with the restricted idea of cast-iron arch bridges for thirty-five years, the two younger men experimented with a wide variety of forms, while at the same time developing railway machinery and designing whole systems of transport. Brunel, in particular, with restless energy, pursued so many enterprises in this age of railway mania that his astounding talent for inventing form never matured beyond his brilliant early works. Brunel was almost like someone from another and more technologically advanced planet suddenly set down in a backward land and overwhelmed by the opportunity of introducing new ideas.

The lives and careers of Stephenson and Brunel were in many ways parallel: both had distinguished engineer fathers; both, like Telford and Rennie, had no formal engineering education; and both died within a month of each other at a relatively young age. Both men created record-breaking spans that call forth comparisons to Telford’s designs. Such comparisons are valid. But, because Stephenson and Brunel had to consider the new engineering problem of the locomotive load, they also came up with very different solutions and invented very different forms. The new machine forced structural engineers to change ancient ideas about form because for the first time in history, a heavy and dynamic load had to be supported by a light metal form. For Telford and all before him, the primary load had been the dead weight of the structure itself. The problem of design had been the subtle relationship between the form of structure and the forces within it due to its own dead weight; and the size of those forces in turn depended on the form. This led Telford to design cast-iron arches which, like masonry, resist compression well.

The idea of arch form is severely disrupted if a large load, such as a locomotive, can move about on the structure. Moreover, since the railroad must be nearly level, almost like canal viaducts, girders or trusses were often more practical than arches. Such forms, under locomotive loads, must resist tension and vibrations. The danger of cast-iron girders for railway loading was tragically demonstrated when, in May 1847, Stephenson’s cast-iron girder bridge over the Dee River at Chester collapsed with a passenger train on it.² Such events stimulated the search for new forms in wrought iron. Both Stephenson and Brunel set about to find such forms and, even though they did not fully succeed, their struggles did produce two great bridges, which characterize the end of British dominance in nineteenth-century structural art.

Robert Stephenson

Stephenson’s father, George Stephenson (1781–1849), rose from being an uneducated mine worker in Newcastle to becoming the designer of the world’s first successful steam railway in 1825. He worked closely with his son, designing everything from locomotives to rail bridges. Many of their early iron bridges reflect Telford’s arch forms, but in his last and greatest works Robert Stephenson struck out on his own and created the straight tubular form. Both major examples of this form appeared, symbolically enough, next to the two monumental Telford suspension bridges, one at Conway in 1849 and one at Menai in 1850. Robert Stephenson’s last request was that he be buried next to Thomas Telford, and so he was. To this day his remains lie next to those of his mentor, in Wales and Westminster.

Stephenson’s struggle with form succeeded technically but not aesthetically. In the Britannia Bridge at Menai, the two vertical-wall iron girders were integrated by horizontal plates top and bottom to
form a hollow box through which the trains ran. The straight horizontal iron box appears to be a solid mass carried by three straight vertical two-eyed stone towers looming over 200 feet above the water.

These towers reflect Stephenson's uncertainty; he had initially planned to build a suspension bridge with a very stiff horizontal deck to prevent oscillations such as those from wind observed on Telford's Menai Bridge and those from the dynamic hammering of locomotive wheels. In the end, the deck was stiff enough not to require cables even though the towers still stand ready to receive a suspension system. This extra, unused security characterized both the immense industrial wealth in Britain up to the Great Exhibition and the inherent conservative temper of these early engineers. Economy was far less crucial than safety in an age when bridge failures were common and in a society grown wealthy beyond comparison. Stephenson's work has been compared to America's moon flight and proclaimed to be "not the product of the genius of the railway engineer alone, but of the collective mechanical genius of the English nation."

The aesthetic defects of the Britannia Bridge are rooted in the fact that structural art does not flourish when the constraint of economy is removed. Stephenson's tubular bridges were based upon detailed testing but not on a need for minimum materials or low cost. The economic imperative of putting the rail line in service quickly overrode the structural engineer's goal for construction economy.

The history of the Britannia Bridge does, however, exemplify one major feature of structural art, namely, that new designs precede new theories. The Britannia Bridge, like Telford's Menai Bridge before it, shows that "the work of the civil engineer involved not the application of existing theoretical knowledge but the design and development of techniques that provided empirical knowledge" from which later developments could arise.

Also instructive are the contrasts between Telford's Bonar Bridge and Stephenson's Britannia Bridge. Telford had developed his mature iron arch form for the Bonar Bridge in 1810 after working with the cast-iron arch form for over fifteen years. Stephenson brought out the tubular form for his immense Menai design without earlier work to guide him. Telford had to produce an inexpensive design for his highlands bridge, and thus he had to think of economy as he developed his form. But, more essentially, Telford wanted lightness, and he therefore sought to make light structures that were as safe as they were inexpensive. Stephenson seems not to have thought visually in this way. The aesthetic goal of lightness was not, for him, a primary goal. Yet it is in fact crucial to structural art; for the greatest structural artists, the goal of visual lightness is as primary as those of safety and economy.

If we turn now to Brunel, we can see how his aesthetic ideas, being more focused on visually thin structure, directed his work toward designs of even greater technical merit than those of his contemporary.

Isambard Kingdom Brunel

No character in the history of engineering fits so well the popular image of genius as does Isambard Kingdom Brunel. Even his outlandish name, combining his English and French heritage, prophetically signaled someone without peer.

In yet another parallel with Stephenson, Brunel was the son of one of Britain's foremost engineers. When Tsar Alexander had invited Marc Brunel (1769-1849) to Russia in 1821, the Duke of Wellington intervened to keep him in England. Isambard was born in 1806 at Portsea, England, where he grew up. After studying mathematics and watchmaking in Paris for three years, he returned to England, where at age sixteen he began his engineering career, working with his father. In 1824 young Brunel went to work on his father's greatest project, the boring of a tunnel under the Thames. He rose quickly to the position of resident engineer on this monumental construction, but by January 1828 was seriously injured as part of the tunnel gave way. He recovered slowly, and in 1829 his family sent him for recuperation to Clifton, high on the limestone cliffs overlooking the Avon Gorge leading to Bristol.

That his parents would have chosen this dramatic site for his convalescence can only be regarded as providential because it went together with young Brunel's exuberant imagination and the extraordinary coincidence of a bridge competition there in 1829. Brunel, with no previous bridge experience, proceeded to make four different de-
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signs, each of a suspension bridge with a central span far greater than any previous bridge anywhere of any type (spans from 870 to 916 feet). For this reason, the bridge commission felt uncertain about judging the twenty-two designs submitted, and it asked Thomas Telford, then seventy-two, to be the judge. Telford rejected all twenty-two designs; he considered it wrong for the span to exceed that of his Menai Bridge. Undoubtedly, he was as much concerned about wind oscillations as about his retention of a world's record. Telford then made his own design, which included huge Gothic towers down into the valley. Brunel sharply objected to this design in a letter to the commission. Eventually, the commissioners agreed with Brunel's objections. They held a second competition in 1831 and, after some further discussions, gave the design to Brunel. Work began on June 21, 1831, but was suspended when political riots in Bristol made it impossible to raise funds. By 1849 both towers had been completed, but the bridge was not finally built until 1864, five years after Brunel's death.

With the bridge construction at a halt, the youthful Brunel turned to railroads and between 1833 and 1841 directed the design, construction, and operation of the longest major rail line in the world, the Great Western Railway between London and Bristol. It was a grandiose project: of broad gauge, it contained the world's longest railway tunnel (nearly 2 miles) and the world's longest spanning brick arched bridge at Maidenhead. In 1854 Brunel designed and built Paddington Station, the London terminal for his railway, and in 1859 he completed the Saltash Bridge near Plymouth for the extension of that rail line from Bristol to Exeter to Cornwall.

Brunel's virtuosity as an artist in structure shows in these vastly different types of construction, for example, in the light, elegant intersecting iron vaults over the Paddington train platforms (figure 3.1). But his relatively short life and his extraordinarily varied mechanical engineering designs did not allow him the time to carry his structural ideas as far as Telford had carried his. It was, in particular, the frantic activity always associated with modern machinery that distracted Brunel and even led to his premature death. Brunel not only laid out entire rail lines, but he designed the rails, the switching, and the station with buildings, and he thought deeply about locomotive design. At the same time, he began designing the world's largest iron ships; these proved both technically too far ahead of their time and financially disastrous.

FIGURE 3.1
Paddington Station Roof, London, 1854, by Isambard Kingdom Brunel. This iron arch roof shows Brunel's use of metal in the design of intersecting vaults for covering the train shed at the London terminus for his Great Western Railway.

Unfortunately, Brunel usually invested his own money in the ventures for which he was the designer.

It is typical of the fundamental distinction between the two sides of technology—structures and machines—that whereas the former are static and permanent, the latter are dynamic and transient. Barely a trace remains of Brunel's major machinery—the ships and the locomotives—and none are currently in use. Most of his major structures, on the other hand, still stand and serve their purpose as well today as they did over a century and a third ago. The structures, of course, have needed maintenance, and over time some parts have been replaced; but, as with Telford's works, Brunel's structures are the permanent symbols of their age, the last great era of British world dominance in politics, science, machinery, and structures. It was in the 1850s that British dominance climaxed, and Brunel's works—in all their grandeur, self-confidence, and mixed success—characterize that climax.

If Telford was engineering's Bach—creating patiently and with
unparalleled productivity—then Brunel was its Wagner. Telford was essentially a servant of the state, paid a fee to produce almost weekly a new design. Brunel was, by contrast, a private entrepreneur who designed entire networks. Telford’s life holds little fascination apart from his works, whereas Brunel’s life is ultimately as exciting as the objects he created. Telford belongs to a classic tradition, Brunel to the romantic age. No one thought of Telford, during his lifetime, as an artist in the same sense as they thought of Turner; yet Brunel struck his contemporaries as both a genius and an artist. He was, however, an engineering artist, a fact not well recognized then or now.

Because he was an engineering artist, Brunel’s works were based upon meticulous detail, sound technical training in the field, a love of the visual objects of technology, and a clear understanding of politics. His biographer Rolt, among others, has compared his sketch books to those of Leonardo and his personality to that of Michelangelo, “to the genius of deep, violent, colossal, passionately striving natures.” He has always been thought of in Britain as a Renaissance man. And yet, his biographer, Rolt, errs in stating that “he and his generation bequeathed a sum of knowledge which, like his great ship, had become too large and too complicated to be mastered any longer by one mind. . . . The result has been that while the collective sum of knowledge has continued to increase at a prodigious rate the individual sum has so seriously diminished.” Rolt, implying that only lesser men followed, or could follow, Brunel, limits his field of vision to Britain, where indeed Brunel had no successor; he misses the basic fact that, outside of Britain, Gustave Eiffel and numerous others who came after Brunel not only knew more than he but created greater and sometimes more beautiful works. This qualification having been made, however, it can be said that no other structural artist has attempted such a variety of work as Brunel or worked on such a scale.

The Tension between Structural Art and Business

Brunel’s career illustrates a characteristic of structural artists in that many times their energy and imagination deflected their design talents away from buildings and bridges toward nonstructural designs. Nearly all of the greatest structural artists have been so inventive and many-sided as to involve themselves in ventures that led away from structural design. The temptation into other areas is not motivated solely by artistic factors. It arises also because structural art is the prototypical art of an industrial–democratic revolution. As such, structural art politically symbolizes service to the building of a common life; its ethic is a servant ethic that eliminates the possibility of great financial profit. Brunel clearly recognized this and felt the paradox that his greatest works brought him his smallest financial return. As he put in his Journal, “One thing however is not right; all this mighty press brings me but little profit—I am not making money. I have made more by my Great Western shares than by all my professional work—what is my stock in trade and what has it cost and what is it worth?” The dilemma of which Brunel speaks has existed since the Industrial Revolution, which coincides with the emergence of structural art.

In other arts, such as modern sculpture and painting, the rewards for success can be comparable to those in business: Picasso died a millionaire and Henry Moore’s profit is immense. But no twentieth-century structural artist can make anything but a modest single professional fee from his best works. He therefore looks to other types of business in order to gain financial independence. In the nineteenth century, Washington Roebling wrote about his father, John Roebling, the designer of the Brooklyn Bridge: “My father always held it as a necessity that a civil engineer (one of the poorest professions in regard to pay) should always, when possible, interest himself in a manufacturing position.” The reason, of course, was not merely to leave design and make more money; on the contrary, “the rope business being established [John A. Roebling’s wire rope manufacturing] . . . his ambition prompted him to greater efforts [bridge design].” In the best survey of civil engineering in nineteenth-century America, Daniel Callhoun emphasizes the fact that engineers came increasingly to see themselves as servants of business. If so, this perception may account in part for the relative lack of structural artists in the United States, especially when compared to such small countries as Switzerland where the idea of design for the public welfare is stronger.
Brunel and Stephenson

As should already be obvious, despite certain similarities in their careers, there were great differences between Brunel and Stephenson. Samuel Smiles, the famous Victorian biographer of British engineers, contrasted Brunel and Stephenson together with their respective fathers: "The Stephensons were inventive, practical, and sagacious; the Brunels ingenious, imaginative, and daring." Smiles proceeds to generalize those traits in national terms. "The former were as thoroughly English in their characteristics as the latter perhaps were as thoroughly French."  

The contrast Smiles makes between the practical and the imaginative is valid in a certain business sense but not in the sense of structural art. In terms of business ventures, Brunel dared much and perhaps overextended himself. He simply tried too many different ventures at one time to be able to avoid, in some of them, disastrous failure. But in structural design, Brunel was as practical as Stephenson. In fact, in his structural art, Brunel's daring and sagacity reinforced each other. This conjunction of daring and sagacity, of the practical and the imaginative, is characteristic of all great structural art.

The difference between Brunel and Stephenson, then, is the difference between a not fully mature structural artist and one who, although more mature, was less artistic. This difference emerges when we compare the greatest bridge of Brunel—the Royal Albert Bridge at Saltash—with Stephenson's greatest bridge—the Britannia Bridge. Some of the aesthetic defects of the Britannia Bridge were evident in the comparison made earlier with Telford's Menai Bridge. The present comparison is even more direct and therefore even more revealing. Both Stephenson's and Brunel's bridges are for railway and both have essentially the same main-span lengths. Stephenson's Britannia Bridge, completed in 1850, has two main spans of 460 feet each and two side spans of 230 feet. Brunel's Royal Albert Bridge at Saltash has two main spans of 455 feet each and seventeen shorter approach spans ranging from 69.5 feet to 93 feet.

The first measure of comparison is the amount of material used for main spans. The Britannia main spans contain about 7,000 pounds of iron per foot of length whereas the Saltash main spans contain 4,700 pounds of iron per foot. Thus, the Brunel work uses substantially less material. A second quantitative measure is cost. This measure is less precise because the locations are different, the time of construction not the same, and the total length and span lengths are different for the approaches. Nevertheless per foot of single track, the Brunel bridge cost about half that of the Stephenson bridge. Thus the lighter work was also the cheaper.

The primary reason for the large differences in iron and in cost lies in the main structural form chosen. At Britannia, the span has solid walls and a total depth (from top to bottom of the box) ranging from 27 to 30 feet; at Saltash, the span is open and the depth (distance between top tube and bottom chain) is about 62 feet at midspan. The greater depth at Saltash means that less material is needed; the solid wall at Britannia puts extra material where it is not needed. Both engineers had Telford as their model, and both believed that such long spans required a suspension bridge. Yet they both knew that the suspension form needed extra stiffening for a locomotive loading. Stephenson's practical approach to this problem was to invent a hollow box form for the railway. He saw this at first only as the stiffened deck of a suspension bridge, but detailed tests convinced him later that no cables were needed and the deck could stand alone. Brunel's daring approach was to imagine a new form in which the arch tube could stiffen the cables and where the cables could tie together the arch ends. In both bridges the towers rise well above the roadway; but at Saltash their function is to connect the arch and cables, whereas at Britannia, standing free above the hollow tubes, they serve no purpose.

Finally, the Saltash span shows visually how the loads are carried: by compression down the arch and tension up the cables (figure 3.2). In the Britannia span, such a visual statement is missing; it looks equally stiff from end to end (figure 3.3). The Saltash is a highly expressive form; the Britannia hides its form in deference to a uniformity which its designer argued was suited to construction. But the justification for construction suitability lies in economy, and the Saltash, as we have seen, was less costly.

In appearance the two works could hardly be more different, considering their similarity of scale and use. A comparison of the three major visual components common to all bridges—the supports, the span, and the approaches—shows this difference. In the Britannia, the
FIGURE 3.2
The Saltash Bridge over the Tamar River near Plymouth, England. 1859, by Isambard Kingdom Brunel. The two main spans of 455 feet each are carried by a combination of tubular arch and chain cable. The structure is lighter and was less costly than the Britannia Bridge.
supporting towers are purely vertical, extend well above the girders, and are given a decorative cornice. In Saltash, the towers extend only to meet the span and they have no decoration. As for the span itself, at Britannia the girders are visually solid and give no expression of structure. At Saltash the expression of structure is pronounced but ambiguous: the form is complicated by being in effect two distinct forms, the arch and the cable. The span, however, is open and all parts are clearly articulated: the horizontal deck, the vertical suspenders, and the two spanning elements, arch and cable. The abrupt change between main spans and approaches sets off the Saltash arch-cable although the visually continuous horizontal deck girders do express some integration of the many spans. At Britannia, the massive stone entrances signal a complete break between approaches and main spans, as well as emphasizing the decorative vision of this bridge as a national monument, a vision the immense sculpted lions on the approaches confirm.

The Saltash stands for the daring, experimental, even nautical verve so central to the rise of Britain as a world power; the Britannia characterizes the type of self-conscious symbol that great powers often build when their dominance is already on the wane. Saltash is a strong visual stimulant, inelegant and idiosyncratic; Britannia deadens the art of structure, despite the abstract elegance of its composition. As we shall see later, forms like the Britannia appealed to many twentieth-century designers as they struggled to come to terms with technology. But when they followed such nonstructural directions, their works, too, tended to be wasteful of material and costly to build.

There is another symbolism to these two bridges, though it resides more in the personalities of the two designers than in the physical structure of the works. For all the differences of character that had resulted in two such different bridges, and for all their almost continuous public confrontation and debate on engineering issues, Brunel and Stephenson maintained a steadfast friendship throughout their lives.

"It is very delightful," Brunel had written after an evening spent with Stephenson in May 1846, "in the midst of our incessant personal professional contests, carried to the extreme limit of fair opposition, to meet him on a perfectly friendly footing and discuss engineering points." When Stephenson had needed his support and advice at the floating of the first huge tube of his Britannia Bridge across the Menai, Brunel had waived all his engagements and hurried north to be at his friend's side.

This private friendship in the face of public rivalry seems to reflect the view that these two men had of their work, and the context into which they put it, and thereby, to express the ethic of dedication to public welfare necessary to the structural artist.

To follow the progress of structural art through the age of iron, we must turn now to France, where the greatest of all engineers in iron was beginning his career as Robert Stephenson and Isambard Kingdom Brunel were ending theirs.