Navier and the Introduction of Suspension Bridges in France

ANTOINE PICON*

The appearance of the first suspension bridges in France in the years 1820–1830 marks a turning point in the debate over civil engineering management and construction. Imported from England, the new technique in effect raised a whole clutch of questions as much concerned with the role of applied mathematics in the design of structures, and with methods of construction, as with the aesthetics of civil engineering projects. In view of the way these questions converged one can thus talk of a genuine change in the constructional paradigm. It is this change in paradigm which I wish to stress in the following pages, rather than the stages in the spread of suspension bridges, already described on various occasions by historians of technology [1]. Seen from this perspective, the role played by Claude-Louis-Marie-Henry Navier (1785–1836) is a very particular one. As a pioneer in the study of the resistance of materials he was to take an interest in all the problems posed by suspension bridges, with varying degrees of success, as we shall see. His successes as well as the failures can thus serve as the principal channel for my argument.

The French Civil Engineering Tradition

To understand the factors involved in the introduction of suspension bridges it is obviously necessary to begin with a rapid survey of the French civil engineering tradition which preceded it. In relation to this tradition suspension bridges display both differences and continuities, which are not always easy to disentangle.

For French engineers of the first half of the nineteenth century the ideal bridge was built of stone, still modelled quite closely on the greater projects of the preceding century by Regemortes, Perronet, de Voglie or Gauthey [2]. This bridge type, with slender piers and low segmental arches, was resolutely monumental in character. Even if the almost 'gothic' slenderness of its piers transgressed certain canons of classical aesthetics, such a structure was still tied to the Vitruvian tradition and the principles of proportion which derived from it. A costly structure, several million francs of the period, it necessitated highly sophisticated construction, based on the stereotomic skills characteristic of the French building tradition [3]. True masterpieces of stonemasonry, the bridges of Perronet, Gauthey and their successors in fact constituted a technical lineage scarcely susceptible to radical innovation, and hardly exportable either (to which the scarcity of works of this type executed in England bears witness) [4].

When construction in stone was rejected for reasons of economy engineers built bridges in wood, much simpler but much less durable [5]. In spite of the interest shown for a long time in Swiss bridges, formed from an assemblage of curved wood slats [6], timber structures mostly resembled the models found in eighteenth century

*Translation by Maxine Copeland.

treatises, such as the *Recueil de différents projets d'architecture de charpente et autres concernant la construction des ponts* by the engineer Pitrou [7].

The relatively fixed character of French constructional techniques seemed therefore to leave little room for innovation. Furthermore, was not the design and execution of construction projects the preserve of the engineers of the Ponts et Chaussées, members of an often hidebound organisation [8]? But the situation was not as simple as it might appear. The seeds of renewal in fact already existed, even before the desire to imitate England served to precipitate the events of the early years of the Restoration.

In the first place the boldness of certain stone constructions contributed to the replacement of the static approach to structural problems, characteristic of the classical period, by a more dynamic outlook. This new outlook led as much to the rationalisation of certain on-site operations as to the first attempts to use applied-mathematical calculation in the design of structures. The work of someone like Perronet, on the eve of the Revolution, displays particularly clearly the new factors which emerged in this way [9]; his successors were to take up where he left off. Secondly, in an altogether different field, timber bridge construction precipitated other structural questions, linked to the notion of assemblage. Above all, however, they emphasised the importance of economic considerations. Masonry or timber, expensive monuments or more modest structures, these new attitudes constituted the backdrop against which the first French suspension bridges made their appearance. In an attempt to reconcile monumentality and economy Barnabé Brisson, soon to become Professor of structural engineering at the Ecole des Ponts et Chaussées, published in 1815 an *Essai de comparaison du point de vue économique des ponts en pierre et des ponts en charpente* [10], which clearly set out the different aspects of the dilemma.

New Factors

From 1815, immediately after the fall of the Napoleonic Empire, French engineers suffered a severe blow to their pride when they discovered the lead taken by England. English inventiveness, the original solutions found for structural engineering problems, and their economical character, all fascinated the first engineers from the Ponts et Chaussées sent on missions across the channel. One such engineer was Joseph Dutens, who published in 1818 his *Mémoires sur les travaux publics de l'Angleterre* [11].

This fascination was part of a much more general change in perception. From this time the French élite began to admire British institutions and society, after having fought against them for so long. The 'collaborative spirit' of English capitalists particularly fired their imaginations. It remained to be seen how this spirit of initiative could be introduced on the continent in order to make up the lost ground which was constantly under scrutiny.

The above objective presupposed the removal of a series of obstacles, such as the traditionally difficult relations in France between the state and the private sector. It was made all the more necessary by the new needs which were emerging in all areas. In the case of communication links, for example, the *départments* and the *communes* were demanding ever more roads and bridges. Inventors of construction systems claimed to be simple and economical were legion in this field. Around 1820, for example, a design for a bridge secured with guys was proposed by the architect Poyet to municipalities wishing to have one at low cost [12]; an artillery officer for his part invented a mixed method, consisting of iron and wooden slats, which foreshadowed the system used soon after by the engineer Polonceau for the Pont du Carrousel in Paris [13].

In this climate of inventive fever, however, several questions remained unanswered. In order to catch up with England was it first of all necessary to imitate that country down to every last detail? On the contrary, the lessons England could teach might be more effective if adapted somewhat to the particular habits and spirit of her principal competitor. To this end, could not the process of modernisation be accelerated by making use of the French science of applied mathematics, which had been a fine art since the eighteenth century? If practical developments were above all English, the theory behind them was often provided by French scholars and engineers, who had access to institutions like the Académie des Sciences or the Ecole Polytechnique which could help them in such a task. At the Ecole Polytechnique, in particular, future engineers received quite a thorough scientific training as a preliminary to any specialisation [14]. Was it not worthwhile making use of their knowledge in order to speed up the spread of innovations?

We can see that in the course of the first half of the nineteenth century the problem of the relationship between pure science and its practice application took on a completely new importance. It is not surprising that Navier very quickly came to the fore in this situation. The whole of his work in fact seems to come under the heading of the reasoned application of scientific principles to the practice of engineering.

A Brilliant Career

Made an *ingénieur ordinaire* at the Ponts et Chaussées in 1807, after having passed through the Ecole Polytechnique and the Ecole des Ponts [15], Navier became known by publishing between 1809 and 1816 the writings of his uncle and teacher Gauthey. The latter had been *ingénieur général* des Ponts, a celebrated civil engineer and the creator of the Canal de Bourgogne [16]. Alongside the work relating to his ordinary post Navier republished in 1819 the first volume of *Architecture Hydraulique* by Bélidor, the *vade-mecum* of the engineers of the Enlightenment, to which he had added numerous notes of his own relating to the general principles of mechanics and the theory of mechanical engineering [17]. In the same year he became professor of mechanics at the Ecole des Ponts et Chaussées and tried to raise its scientific standards by making systematic use of analysis in his teaching [18]. In 1821 his *Mémoire sur les lois de l'équilibre et du mouvement des crops solides élastiques* constituted the real foundation stone of the study of the resistance of materials, even though it was still based on Laplace's molecular theory which Cauchy was to refute with such success soon afterwards [19]. Made a member of the Académie des Sciences in 1824, Navier also began to pursue a career as a practising engineer, directing various construction projects, amongst which was the Pont des Invalides which will be discussed later. For his superiors both his theoretical and his practical knowledge made him the natural candidate for selection, in 1821, to investigate the question of suspension bridges.

The 1823 Report and Treatise on Suspension Bridges

French visitors to England around 1820 could see Berwick Bridge, built by Samuel Brown, with a deck held by flat-link chains of wrought iron. In addition, engineers also had access to the *Treatise on Bridge Architecture*, published in 1811 by the Englishman Thomas Pope, which contained the description of the first suspension bridges carried out by Finley in the United States. In spite of Dutens' obvious hostility towards suspension bridges in his *Mémoires sur les travaux publics de l'Angleterre*, the impulse to introduce the technique in France was strong. This was because it could meet the need for solid and economical structures, which could not be satisfied either by stone or timber bridges, or by the first metal bridges in Paris, which had proved particularly costly [20]. In order to form an opinion, the Director General of the Ponts et Chaussées Louis Becquey therefore decided to send Navier to England, entrusting him with the task of examining the question. Navier made two tours, in 1821 and 1823, before making known his conclusions in his *Rapport à Monsieur Becquey,...; et Mémoire sur les ponts suspendus,* the publication of which in 1823 represented a decisive event. Having gathered and examined all the available information relating to the new technique Navier recommended its adoption. The clarity and rigour of his arguments quickly persuaded the authorities to approve the construction of suspension bridges.

After a brief summary of the main results of his work, for the benefit of the Director General of the Ponts et Chaussées, the engineer goes into the details of his investigation. He begins with an historical section, in which we learn in particular that suspension bridges originated in the mountainous areas of South America and Asia, where rope bridges were used for crossing various chasms [21] (Fig. 1). The true inventor of modern suspension bridges, however, remains the American Finley. In England Navier examines in turn the schemes for bridges across the Mersey and the Menai Straits by Telford, the bridge at Berwick, two projects for suspension bridges for the Island of Bourbon by Brunel, not to mention various proposals by Stephenson. Returning to France, Navier ends his historical account with a description of the footbridge built at Annonay by the Seguin brothers (who were soon to carry out the first French suspension bridge at Tournon) as well as the suspended aqueduct carried out by the Comte de Chabrol. A certain lyrical quality appears here in the text, where he concludes this essentially descriptive section of the work.

> It is likely that the use of suspension bridges will soon become widespread; by this means we will create communication links in places where it seems at present impossible... These structures will exhibit great elegance of form, invariably determined by the natural laws of equilibrium; they could also, if designed by a talented engineer, contribute to the embellishment of capital cities, or, suspended across precipitous valleys, they could produce the most imposing of effects in the picturesque settings of mountainous areas. These edifices will present to the imagination a vision of the power of the human arts overcoming, for the public good, great obstacles set up by nature and long held to be invincible. [22]

According to Navier, the essential characteristic of suspension bridges lies in their subjection to the "natural laws of equilibrium". It is these laws which he endeavours to explain in a second section, using all the resources of mathematical analysis, and in particular the methods of integration developed by the celebrated scientist, Fourier, when he was researching into the transmission of heat [23]. In order to do this Navier first of all deals with the equilibrium of evenly loaded chains suspended between two points along a horizontal line, which are found to take a noticeably parabolic shape. He then establishes the formulae for evaluating the tensile forces of the suspension chains when at rest in each type of arrangement. However, he is particularly interested in the movements produced by the passage of carriages across the structure. He breaks this down into oscillations arising from the flexibility of the chains, and into vibrations related to the elasticity of the iron. He then uses calculations to show that the effects

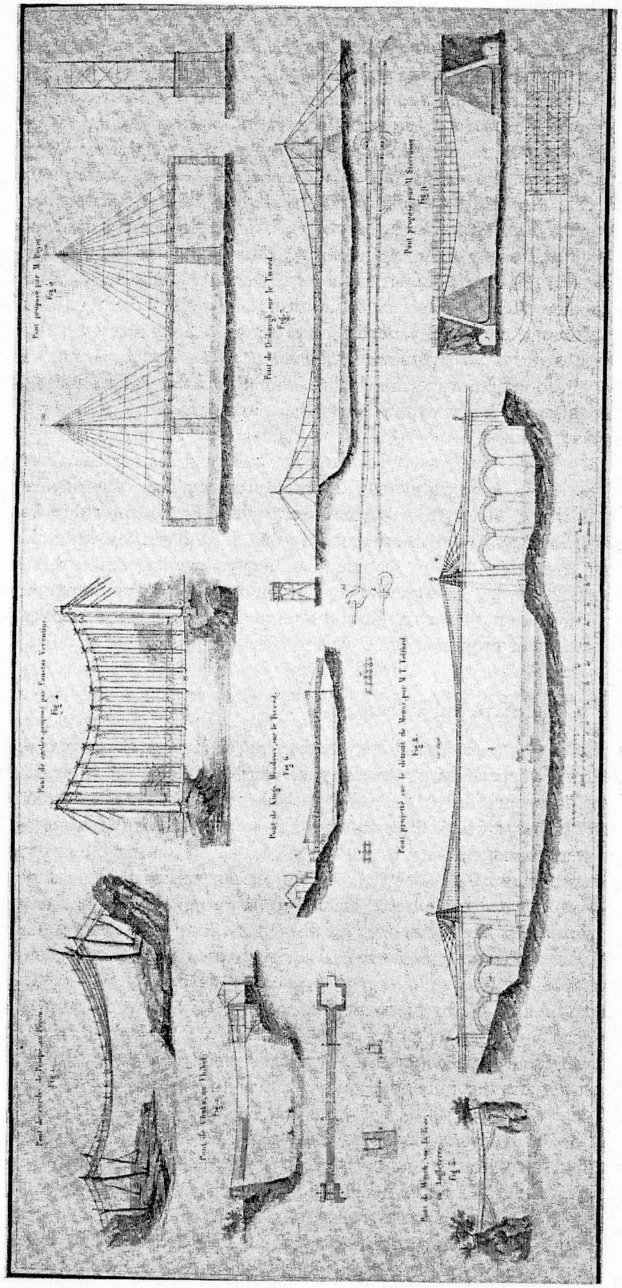

FIG. 1. C. L. M. H. NAVIER: Suspension bridges from the primitive rope bridges of the Indians to Telford's project for the Menai Straits (from *Rapport et Mémoire*, 1823).

of the passage of carriages are less noticeable when the bridges are heavier and longer, and their chains suspended in a shallower curve. Thus, in contrast to traditional construction, suspension bridges gain in stability in proportion to their length. It therefore becomes possible to envisage the crossing of almost 500 metres with a single span, instead of the 60 or so metres range of the widest stone arches.

Next, on a more general level, suspension bridges can be considered more flexible systems, very different from stone or timber structures, since they can undergo substantial structural distortions without suffering damage. The whole problem consists of establishing a limit for these distortions, by investigating in particular the strength of the iron needed to withstand them. At the end of his *Rapport et Mémoire* Navier summarises all the experiments carried out in this field, both in England and in France, by the engineers Barlow, Telford and Duleau, and also by the Seguin brothers, whose findings, although empirically derived, were not without interest [24]. These experiments show that, in order to guarantee the safety of the structures one wishes to erect, all one has to do is determine the thickness for the chains whereby their failing stress always remains greater than three times the maximum tensile stresses they are required to bear.

The theory developed by Navier was still far from exhausting the question of suspension bridges. In concentrating on the chains the engineer was neglecting, in particular, the effects of the rigidity of the deck, whilst in contrast this was what Rankine stressed in his treatise on mechanics of 1858 [25]. The *Rapport et Mémoire,* however, displays a mastery of the technique of analysis quite remarkable for the period. Above all it expresses the hopes of a generation of French civil engineers who saw the reasoned imitation of the English model and the systematic application of mathematics as carriers of progress.

Towards a New Constructional Paradigm

Navier's work also marks an essential step in the transition from the *modus operandi* for civil engineering inherited from the classical period to the new approach called forth to replace it. More precisely, it seems that the introduction of suspension bridges was accompanied by the first sketching out of a new constructional paradigm.

In the seventeenth and eighteenth centuries the methods used by engineers for determining measurements were clearly related to their desire for monumentality. These methods were in most cases based on the use of proportions. The creation of a sense of solidity in a work thus depended on the observation of a certain number of rules relating the proportions of the load-bearing elements to those of the supported elements; for example, the famous 'corner theory' of de la Hire, still in use in Navier's time, expressed the breadth of the piers supporting an arch in terms of the diameter of the arch [26]. Accordingly, the engineer's art consisted of playing with the rules, of breaking away from them to some extent, "by proportionally increasing or decreasing the parts" as most authors recommended, in order to adapt the design to the particular circumstances.

In this situation bridge design was still derived from very architectural models, which were modified in a tentative and piecemeal way, through a continuous process of negotiation between the ideal and current design practices. Such a process corresponded to the way in which an architect chose to deviate from the rules of proportion given in the treatises of Scamozzi, Palladio or Vignola, in order to create an edifice in his own style [27]. Constructional theory in effect provided a set of average values, serving as the basis for constantly evolving negotiations, whilst on the other hand the practice of construction was difficult to encapsulate in a system of invariable prescriptions.

It is this definition of theory and practice which brings Navier's *Rapport et Mémoire* back into the discussion, for in it he substitutes analytical calculation for the use of proportions, and above all replaces the search for average values by fields of validity, within which laws apply which accord with experimental data. To do this Navier introduces the notion of limits which allows him to determine fields of validity for each of his formulae. In fact, since in the majority of researches relating to construction methods "the results of the solutions normally satisfy limits which natural forces cannot exceed . . . all the builder needs to know is what these limits are" [28]. Thus, instead of providing a sort of centre of gravity for practical applications, the theory aims to establish *a priori* limits for the degree of freedom allowed to the practising engineer; this done, the practical work carried out by the latter will accord with the results of calculation.

Such a development derived in part from the essential nature of the new bridging method, in which the laws of mechanics could be more easily perceived than in stone construction. At the same time a certain tendency towards dematerialisation was expressed through the suspension bridge, which no longer derived from a slowly perfected spatial model. Rather, it derived from an operational principle sufficiently general to sanction the most visually diverse of versions, including those covered by Navier's historical account.

What had been discovered, then, was the possibility of defining a system of constructional norms, based on mechanical requirements which were susceptible to testing. It is therefore not in the least surprising to see Navier's study serving as the basis for a series of deliberations within the Ponts et Chaussées about the question of these norms. This task was made even more necessary since the construction of many suspension bridges would have to be given over to the private sector [29]. In this area too an important change was taking place, in France at least, for the construction and maintenance of the majority of civil engineering works was traditionally the preserve of the Ponts et Chaussées department. The controversy between pure science and practical application which the engineer claimed to be resolving, through the notion of limits to natural forces and the establishment of structural norms it facilitated, could therefore not be separated from the public/private debate which was occupying people's minds at the same time. To speak of a new constructional paradigm comes down to encompassing in a single concept the evolution of building techniques, the transformations in the relationship between theory and practice which it entailed, and the alterations in the socio-economic organisation of public building works which accompanied it.

The Failure of the Pont des Invalides

In his *Rapport et Mémoire* Navier had proposed a project for a suspension bridge over the Seine in Paris, opposite les Invalides, which he regarded as an application of his theoretical researches (Fig. 2) [30]. The bridge would consist of Egyptian style piers, 3 metres in diameter and some 15 metres high, spaced 170 metres apart, across which passed chains, each formed of 9 courses of oblong wrought iron links. The chains would support a platform 9.5 metres wide, weighing nearly 600 tonnes. As we can see, it was an ambitious project, whose range almost equalled that of the largest distance spanned at the time, by Telford at the Menai Straits. Approved in 1823 by the Ponts et Chaussées authorities, the contract was awarded to a limited liability company in the following year. Work began immediately, thereby apparently justifying the convictions of the engineer, who claimed to have definitively resolved the divorce between theory and practice, unworthy of a "body as enlightened as the Ponts et Chaussées" [31].

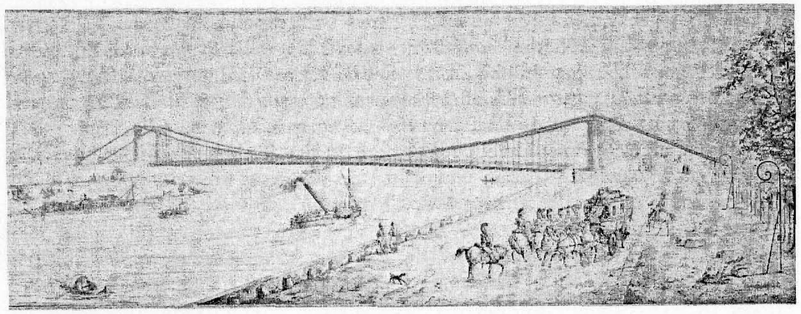

FIG. 2. C. L. M. H. NAVIER: Perspective of the Invalides project (from *Rapport et Mémoire*, 1830 edition).

Unfortunately for Navier, things began to go wrong on the building site: a slight movement in the foundations was soon aggravated by flooding on the night of 6–7 September 1826, resulting from the bursting of a water pipe, just when the suspension system had been put in place. The stability of the structure was thereby gravely compromised and they were forced to dismantle the chains. The damage was entirely repairable; however, perceiving the detrimental visual effect the structure's Egyptian columns might create in front of les Invalides, the Conseil Municipal de Paris decided purely and simply to cancel the scheme, which at the same time deprived Navier of any chance of vindicating himself.

For the author of the *Rapport et Mémoire* the blow was made even worse by the fact that the Seguin brothers, entrepreneurs from Annonay in the Ardèche, had the previous year just completed the first suspension bridge in France, at Tournon (Fig. 3). Whilst giving credit to Navier for his mathematical skills, Jules Seguin, in his 1826 treatise *Des ponts en fil de fer,* stressed the more practical nature of his own approach, which in particular made it more responsive to technico-economic factors [32]. In order to carry out their scheme, had not the Seguin brothers visited the main iron manufacturers in Burgundy, thus displaying a knowledge of industrial processes which the government engineer lacked? The number of new constructional techniques associated with suspension bridges were soon to show that links with industry were essential.

In the meantime Navier was judged harshly by his contemporaries, who had often been irritated by his ambitious claims. The press hounded the engineer, accusing him of incompetence. Although supported by his department, he was criticised by individuals such as Brunel. In a letter addressed to one of his French correspondents Brunel reproached Navier for not having taken into account the expansion of metal, and especially with having overloaded the whole of his structure, whilst in contrast Jules Seguin had "achieved the greatest strength with the lightest possible structure" [33].

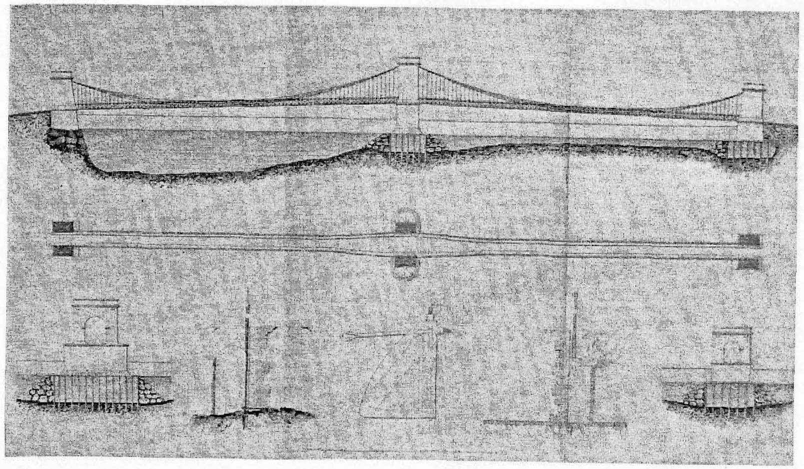

FIG. 3. J. SEGUIN: Bridge at Tournon (from *Des ponts en fil de fer,* 1826).

Many critics, however, attacked the new method of construction, rather than the project itself. The aesthetics of suspension bridges were particularly subject to attack, which Navier was to attempt to refute.

A New Aesthetic

The question of cost in effect constituted the most radical challenge to traditional principles of design in civil engineering. In their slenderness, which the eighteenth century would have termed 'gothic', and in the clarity of their new structural system, suspension bridges were deviating irredeemably from the principles of classical architecture. Were the autonomy of each part and the analytical character of the structure compatible with the rules of propriety which ought always to be present in the engineer's mind? With this type of structure appeared the unmistakeable phenomenon of delocalisation, since from then on bridges could largely break free of the constraints imposed by the site. Could one define an aesthetic which was outside the traditional stylistic register and which bore little relation to local circumstances?

In a publication of 1827 in defence of his scheme for les Invalides Navier devotes a lengthy discourse to this question, saying first of all that "an iron structure, if its appearance is that of grandeur and simplicity, can as much merit the appellation monument as a stone structure" [34]. After having pointed out that a stone bridge on the same site would have required a considerable raising of the river banks, the engineer enumerates the features of the design aimed at giving his project the quality of lasting magnificence. Thus, the series of links which make up the suspension chains are arranged close together in order to form a sort of sheaf, imposing in effect. Likewise, the simplicity of the structure, "which comprises only a very small number of lines", makes of the bridge "a particular and new type of monument" which is not in the least lacking in grandeur [35]. Following these remarks, which seem unlikely to have convinced the supporters of the dominant aesthetic, Navier returns to more

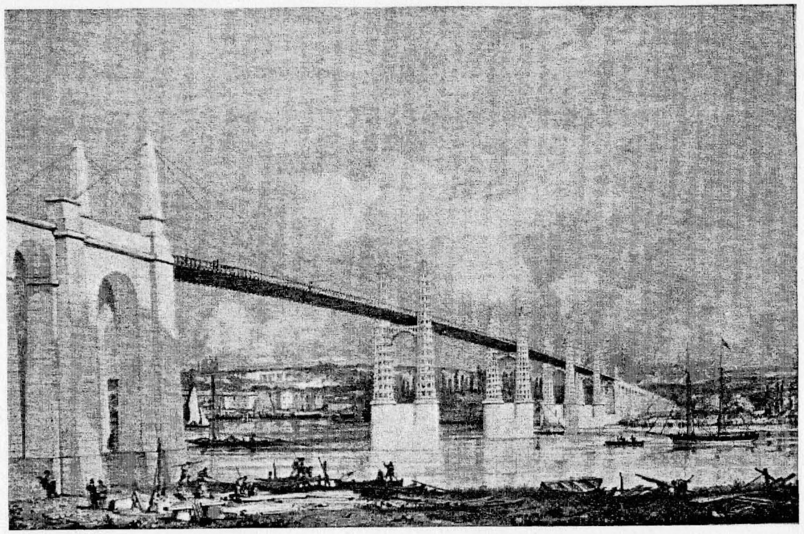

FIG. 4. E. MARTIN: Cubzac bridge, 1841.

traditional arguments. The use of decoration with obvious symbolic content (Egyptian style columns, reclining lions supported by cube-shaped pedestals, with chains hanging from the pedestals) is thus associated with a theory of 'character' similar in appearance to that of the classical tradition.

The fact remains, and this is doubtless the most important point, that the juxtaposition of these two stylistic registers anticipated the eclecticism of the triumphant industrial age. For Navier the essential justification for the Invalides project lay in a constructional principle which permitted the omission of intermediate piers and the provision of clear access to the quays. But the stark functionalism and the originality of the new bridging system could still be reconciled with fanciful ornamentation in a consciously historicist vein. In contrast with the 'very small number of lines' and the overall sense of sobriety suggested by the suspension system and the platform, the masts of suspension bridges carried out in the period which followed were designed in the most diverse styles: neo-classical for the bridge over the Gard at Remoulins, begun in 1829, or medieval for the bridge at Ponts de la Caille on the road between Annecy and Geneva, built in 1839. On the Cubzac bridge completed in 1839, on the other hand, the designers of the project were to achieve plastic expression of great originality, substituting cast iron for masonry in the suspension towers (Figs. 4 and 5) [36]. During the whole of the first half of the nineteenth century suspension bridges thus constituted a favoured experimental field for engineers in search of a new aesthetic. It is in this sense too that one can speak of a new constructional paradigm.

The Spread and Decline of Suspension Bridges

Having burnt his fingers in the Invalides affair Navier abandoned suspension bridges, but this in no way prevented the massive spread of the technique up until the 1850s.

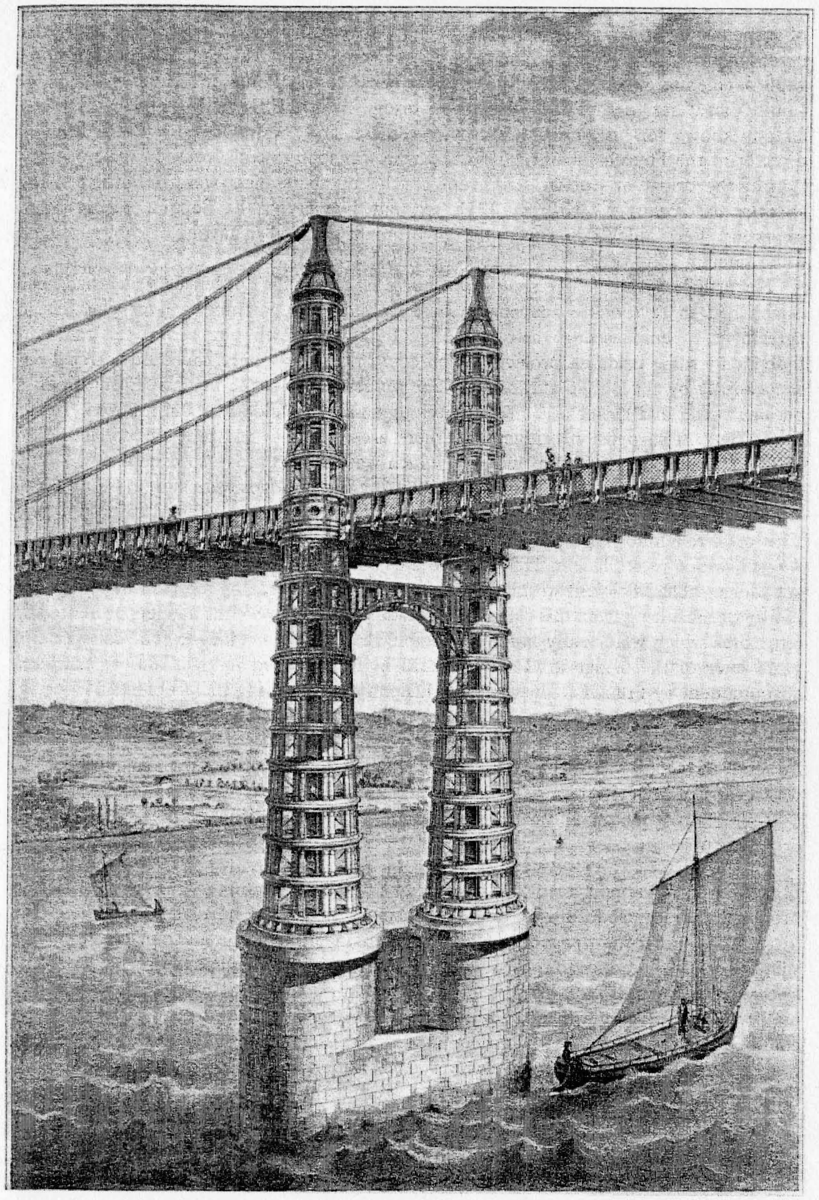

FIG. 5. E. MARTIN: Piers of the Cubzac bridge.

However, a whole series of practical problems were raised, beginning with the question of suspension. Should one use chains, as Navier had advocated, or metal cables of the type which had been used by the Seguin brothers for the bridge at Tournon? Around 1830 a polemic opened up on this subject between the Ponts et Chaussées engineer Louis Vicat, designer of the suspension bridge over the Dordogne at Argentat and already known for his work on hydraulic cement, and the industrialist Emile Martin, director of the Fourchambault ironworks, who was soon to collaborate in the construction of the bridge at Cubzac. Different articles on the subject were published in the *Annales des Ponts et Chaussées* [37], without Navier or the Seguins seeing fit to intervene. Very quickly however, the government decided in favour of cables, judged to be safer in spite of the risk of corrosion [38].

Nevertheless, this debate should not make us forget the consensus which had been established in relation to suspension bridges and their usefulness. Everyone was in agreement in emphasising their economical nature, which put within the reach of individuals some bridging projects which could previously only have been carried out successfully by the public authorities. The process of constructing suspension bridges became better and better organised, matching similar developments in industry. It was in the field of suspension bridges that there arose for the first time the collaboration between structural design and industry which was soon to prove so productive.

From 1830 to 1850–60 an estimated 400 suspension bridges were built in France [39]. But the fall from grace of the new type of construction was to be as rapid as its adoption. This occurred following accidents such as the collapse of the Basse-Chaîne bridge at Angers, which took place in 1850, due to the combined effects of the oxidisation of the anchorage cables, a violent storm and a troop of soldiers marching across in step [40]. The 266 deaths resulting from this catastrophe made people aware of the dangers presented by structures which were really much less stable than they had thought. The collapse two years later of the bridge at Roche-Bernard in Brittany led to their almost complete abandonment by French engineers. The difficulty of mastering the problems of rusting, and the lack of rigidity of platforms in the earliest suspension bridges, was to make rigid metal bridging the preferred technique during the second half of the nineteenth century. As proof of this disenchantment, if it were needed, the platform of the bridge at Cubzac was reconstructed with girders in 1879 by the Eiffel company [41].

Conclusion

In spite of the disappointment felt by the public authorities and those in the engineering profession, the episode of the first suspension bridges had nevertheless allowed the turning of an important page in the history of engineering design and construction. The subordination of practice to the results of theoretical calculation had not turned out to be as complete as someone like Navier would have hoped however. In this context Vicat, in his *Description du pont suspendu construit sur la Dordogne, à Argentat*, published in 1830, could set against questions "which depended almost exclusively on theoretical statics" the practical problems of resistance, elasticity and friction posed by constructional practice [42]. Although the *Rapport et Mémoire* had treated the first aspect *con brio*, the second resisted too reductive an approach. In its relative simplicity the theory developed by Navier proved to be much too ambitious. The shortcomings of the theory, as much as the failure of the Invalides bridge, nevertheless served as a reminder that it is not quite that easy to control all aspects of constructional innovation.

Correspondence: A. Picon, 80 boulevard de Port-Royal, 75005 Paris, France.

References

[1] See eg: D. Amouroux, B. Lemoine, 'L'âge d'or des ponts suspendus en France *1823–1850*', in *Annales des Ponts et Chaussées*, 19 (Paris, 1981), pp. 53–63; G. Reverdy, 'Les ponts suspendus en France', in *Monuments Historiques*, 150–1 (1987), pp. 106–12.

[2] A. Picon, 'Die Vorstellungskraft eines Konstrukteurs: Jean-Rodolphe Perronet und das Modell einer Brücke', in *Daidalos*, 18 (Berlin, 1985), pp. 74–87.

[3] J.-M. Pérouse de Montclos, *L'architecture à la française* (Paris, 1982), pp. 115–6.

[4] T. Ruddock, *Arch Bridges and their Builders 1735–1835* (Cambridge, 1979).

[5] It is necessary to distinguish between bridges composed of masonry piers, with arches and platform in timber, and those built entirely of timber.

[6] See eg: Ruddock, *Arch Bridges*, pp. 35–7.

[7] R. Pitrou, *Recueil de différents projets d'architecture de charpente et autres concernant la construction des ponts* (Paris, 1756).

[8] See eg: A. Brunot, R. Coquand, *Le corps des Ponts et Chaussées* (Paris, 1982); J. Petot, *Histoire de l'administration des Ponts et Chaussées 1599–1815* (Paris, 1958).

[9] Picon, 'Die Vorstellungskraft'.

[10] Ecole Nationale des Pont et Chaussées, MS 1838, B. Brisson, 'Essai de comparaison du point de vue économique des ponts en pierre et des ponts en charpente', 7 Nov. 1815.

[11] J. Dutens, *Mémoires sur les travaux publics de l'Angleterre* (Paris, 1818).

[12] B. Poyet, *Nouveau système de ponts en bois et en fer forgé, inventé par M. Poyet,... Rapports de l'Athénée des arts et de la Société royale des sciences de Paris, développant et constatant les avantages de ce nouveau pont. Procès-verbal dressé par M. le maire de Livry* (Paris, c. 1820).

[13] De Barrès du Molard, 'Nouveau système de ponts à grandes portées ou Moyen économique de construire des arches de toutes grandeurs', in *Journal du Génie Civil*, 1 (Paris, 1828), pp. 90–124. Polenceau described his system in *Notice sur le nouveau système de ponts en fonte suivi dans la construction du pont du Carrousel* (Paris, 1839).

[14] A. Fourcy, *Histoire de l'Ecole Polytechnique* (Paris, 1828).

[15] There is no complete biography of Navier. See Baron de Prony, 'Notice biographique sur Navier', originally published in *Annales des Ponts et Chaussées*, reprinted in Barré de Saint-Venant ed. of Navier's lessons on mechanics (1864), pp. ixl–lj. See also Archives Nationales classification F^{14} 2289^1, Navier's administrative dossier.

[16] E. M. Gauthey, *Oeuvres de M. Gauthey* (3 vols, Paris, 1809–16). Navier was brought up by Gauthey after the death of his father, a member of the Burgundy parliament during the Revolution.

[17] B. Forest de Bélidor, *Architecture Hydraulique* (1st published 1737–9, republished Paris, 1819). Navier also re-edited Bélidor, *La Science des Ingénieurs* (1813).

[18] On Navier's approach to teaching see A. Picon, 'Science de l'ingénieur et aménagement du territoire aux origines du génie civil 1800–1850' (typescript research report, Centre National de la Recherche Scientifique, Paris, 1986), pp. 65–70, 117–23.

[19] For an account of Navier's theories see S.-P. Timoshenko, *History of Strength of Materials* (New York, 1983), pp. 105–7. For the work of Cauchy see B. Belhoste, *Cauchy, Un mathématicien légitimiste au XIXe siècle* (Paris, 1985), esp. pp. 144–51.

[20] Bearing in mind the high cost of French cast iron, metal bridges costs almost the same as stone structures. The pont d'Austerlitz, for example, built by the engineer Lamandé 1800–6, cost 2.5 million francs.
[21] C. L. M. H. Navier, *Rapport à Monsieur Becquey...; et Mémoire sur les ponts suspendus* (Paris, 1823), pp. 3–61.
[22] Ibid. p. 61.
[23] Ibid. pp. 62–176.
[24] Ibid. pp. 211–24.
[25] T. M. Charlton, *A History of Theory of Structures in the nineteenth century* (Cambridge, 1982), pp. 49–50.
[26] See eg J. M. Delbecq, 'Analyse de la stabilité des voûtes en maçonnerie de Charles Augustin Coulomb à nos jours', in *Annales des Ponts et Chaussées*, 19 (Paris, 1981), pp. 36–43.
[27] Links between classical architectural principles and constructional theories were numerous, see engineers such as Bélidor or Frézier on questions of proportion. The famous treatise on stone cutting by Frézier begins with a 'Dissertation historique et critique sur les ordres d'architecture', published separately in 1769.
[28] Navier, *Rapport et Mémoire*, p. xvj.
[29] Tests were instituted to verify conformity to the norms for suspension bridges.
[30] Navier, *Rapport et Mémoire*, pp. 177–202.
[31] Ibid. p. xvj.
[32] J. Seguin, *Des ponts en fil de fer* (Paris, 1826), p. 37.
[33] Ecole Nationale des Ponts et Chaussées, MS 2348, 'Extrait d'une lettre adressée par M. Brunel à M.... Membre du Conseil Général des Ponts et Chaussées', London, 4 Oct. 1826.
[34] C. L. M. H. Navier, *De l'entreprise du pont des Invalides* (Paris, 1827), p. 4.
[35] Ibid. p. 6.
[36] E. Martin, *Pont de Cubzac. Dessins et description des piliers en fonte de fer* (Paris, 1841).
[37] See: L. Vicat, 'Note sur l'allongement du fil de fer soumis à diverses tensions', & 'Nouvelle manière de confectionner les cables en fil de fer', in *Annales des Ponts et Chaussées*, 1 (Paris, 1834), pp. 40–4, 129–42; E. Martin, 'Emploi du fil de fer dans les ponts suspendus', & L. Vicat, 'Observations sur un mémoire de M. E. Martin, touchant les ponts suspendus', in *Annales des Ponts et Chaussées*, 2 (1834), pp. 157–68, 169–72.
[38] Chains had thicker cross-section which rusted less than cables. However they were less economical and their connecting bolts were a weak point. See Leblanc, 'Observations comparatives sur les inconvénients qu'offre l'emploi des fils de fer, ou du fer en barre, dans la construction des ponts suspendus d'une grande ouverture', in *Annales des Ponts et Chaussées*, 1 (Paris, 1835), pp. 315–27.
[39] D. Amouroux, B. Lemoine, 'L'âge d'or des ponts suspendus', p. 60.
[40] Ecole Nationale des Ponts et Chaussées, MS 3130, 'Rapport de la Commission d'enquête nommée par arrêté de M. le Préfet de Maine et Loire en date du 20 avril 1850, pour rechercher les causes et les circonstances qui ont amené la chute du pont suspendu de la Basse-Chaîne, Angers, 9 mai 1850'.
[41] B. Lemoine, *Gustave Eiffel* (Paris, 1984), pp. 57–61.
[42] L. Vicat, *Description du pont suspendu construit sur la Dordogne à Argentat* (Paris, 1830), pp. 2–3.

Science and Art Closely Combined: the organisation of training in the terracotta industry, 1850–1939*

MICHAEL STRATTON

The terracotta industry gained an almost symbolic status in debates concerning architecture and building construction during the Victorian period and the early twentieth century. Moulded and highly ornamental ceramics offered a solution to some of the most pressing practical and artistic challenges faced by architects and builders on both sides of the Atlantic. There was an overwhelming demand for buildings that were highly decorated, colourful and that would appeal to a broad section of the public. This demand was accompanied by the growth of a market for a decorative material that could be easily and cheaply produced, avoiding the expense and organisational problems of employing stone masons and sculptors. Interest in terracotta and faience was crystallised by the crisis that emerged in Britain during the 1850s with the widespread failure of building stones due to attack by sulphurous smoke. Architects became disillusioned over lavishing time and expense on intricate stone carving if it was to be obscured by layers of soot and rapidly loose all its qualities of detail.

There has been a tendency to present iron-framing or other elements of 'functional' construction as the most progressive and contentious aspects of nineteenth century building. However, contemporary critics appear to have been far more concerned with the practical and ethical issues raised by the mass production of ornament, either in the form of cast-iron or ceramics pressed in moulds and coloured with glazes. To understand the strongly divergent reactions to factory made architectural terracotta and its glazed counterpart faience it is necessary to consider the ways in which artists and architects collaborated with the clayworking industry. It is also necessary to understand how mundane brick and pipemaking firms gained the necessary skills to be able to design and model detailing in a wide variety of styles, and how the construction industry reacted to the proliferation of this new material which threatened so many established trades and procedures. It is a story dominated by down-to-earth industrialists and architects, who welcomed any outlet for their artistic aspirations. Most of those involved in the terracotta revival openly accepted the industrial age and its ramifications for architecture and the building industry. Their pragmatism seems to have extended to the way in which they handled practical aspects of manufacture or building construction; both were characterised by make-do and mend to an extent that hardly matched the potential of terracotta and faience for mass-production and pre-fabrication.

Coade Stone to South Kensington

The terracotta revival commenced with the establishment of Coade's Manufactory at

*Based on a paper delivered to the Sixth Annual Seminar of the Construction History Society held in London in September 1987, 'Building Crafts and Conservation'.