[68] For the impact of the sash-window on English architecture see H.J. Louw, 'The Origin and Development of the Sash-window in the Seventeenth and Eighteenth Centuries' (Ph.D. thesis, Oxford University, 1981).

[69] See Wren's critical remarks on the 'effeminancy' of French interior design after his visit to Versailles in 1665 (S. Wren, *Parentalia*, 1750, pp. 261–2), and Evelyn's comments in *Silva* (1670 edition, Ch. XXVI, p. 132).

[70] B. M. Forman, 'The Joyners' Company in 1694', *Furniture History*, X (1974), p. 12.

[71] In the 1692 Poll Tax Returns the percentage of London joiners paying surtax was more than three times higher than that for the carpenters. D. V. Glass, 'Socio-economic status and occupations in the City of London at the end of the seventeenth century', in A. E. D. Hollaender and W. Kellaway (eds.), *Studies in London History* (1969), pp. 382–3, Table 7. The difficulties which the Joiners' Company experienced in 1694, and which are recounted by Forman (see previous note) were of a temporary and mainly administrative nature. The trade was thriving.

[72] H.M. Colvin, *A Biographical Dictionary of British Architects 1600–1840* (1978).

[73] H.C. Darby, 'The Age of the Improver 1600–1800', in H. C. Darby (ed.), *A New Historical Geography of England after 1600* (Cambridge, 1976), pp. 27ff. See also J. Evelyn, *Silva*.

[74] D. Yeomans, 'Inigo Jones's roof structures', *Architectural History* 29 (1986), pp. 85–101; *Parentalia*, pp. 335–339.

[75] C. A. Hewett, *The Development of Carpentry 1200–1700. An Essex Study* (Newton Abbot, 1969).

[76] The records for aliens living in London *c.* 1570–*c.* 1635 shows a very small proportion of carpenters and sawyers: only 8 out of a total of 122 in the peak year for immigration, 1568. The rest were all joiner/carvers and coopers. Scouloudi, 'Alien Immigration', Appendix III.

[77] 38.3%, as opposed to the 11.4% each for the joiners and coopers, the two other large groups of emigrant woodworkers. R. B. St George, 'Fathers, Sons and Identity: Woodworking Artisans in South Eastern New England 1620–1700', in M. G. Quimby (ed.), *The Craftsmen in Early America* (New York, 1984), *passim* but especially Table 11.

[78] Alford and Barker, *Carpenters' Company*, pp. 69–70.

[79] ibid., p. 83.

[80] ibid., pp. 75–77.

[81] ibid., pp. 86–91.

[82] ibid., pp. 81–3, 85–6; H.L. Phillips, *Annals*, p. 26; E. B. Jupp, *Historical Account*, Appendices F and G.

[83] Guildhall Library cat. no. L37 ms. 8332 Ref. 427, 'Opinions of ye Livery & Cominalty of ye Carpenters concerning Joynery read and presented 3 dec. 1672'.

[84] ibid.

[85] TWAS 903/3 Document 38, Newcastle Housecarpenters' Company, 'The Case between the House Carpenters and Joiners'.

Early Nineteenth Century Developments in Truss Design in Britain, France and the United States

D. A. GASPARINI & CATERINA PROVOST

The development of railroads in the 1820s has a particular significance for structural engineers. Railroads created an urgent need for bridges able to carry heavy moving loads and for new building forms for terminals and maintenance facilities. The rush to satisfy those needs accelerated the application of the scientific principles of mechanics in the structural design process and fostered advances in the production and fabrication of iron parts. In particular, by the middle of the nineteenth century engineers understood and applied principles of mechanics to the design of an important structural form: the truss.

Of course trusses were widely used as structures before the nineteenth century. Trusses were constructed primarily of wood, with ropes sometimes serving as tension bars. Hogging structures in early Egyptian boats and indeed much of the strength of a sailing ship depended on truss action of the posts (or masts), the ropes and the hull. Wooden roof-frames, wooden formwork for masonry arches and wooden bridges were often essentially trusses. Notable existing examples of sixteenth and seventeenth century wooden roof frames are those of the Uffizi gallery by Vasari, and those designed by Sir Christopher Wren for the Sheldonian Theatre [1]. Framed wooden bridges were widely used in Switzerland and in Germany in the sixteenth and seventeenth centuries [2, 3]. The design of these successful wood-framed structures in all likelihood evolved by a process of trial and error. Connection details used in some of these structures suggest that the designers understood the sense of the forces in some of the bars (that is, whether they were in compression or tension), but could not compute the magnitude of those forces, on which the rational determination of the cross sectional areas of the bars depends. It must be emphasized however that durable wooden frames required, above all, appropriate connection designs, measures to prevent rotting and provisions for replacing bars and controlling the deflection of the frames.

The concepts needed to analyse statically determinate trusses were defined largely in the seventeenth and eighteenth centuries by Galileo, Stevin, Newton, Varignon and others. Not only could equilibrium equations be written directly by vector operations but also, in the eighteenth century, work and energy principles governing the behaviour of structures were defined. John Bernoulli in 1717 defined the principle of virtual work and by 1744 Leonard Euler developed mathematical techniques (the calculus of variations) to derive equilibrium equations from the principle that equilibrium positions must correspond to stationary values of potential energy functionals. The advanced state of mechanics by the end of the eighteenth century is perhaps best exemplified by Joseph Lagrange's work *Mécanique Analytique* published in 1787. Yet there appears to be no evidence that the principles of mechanics were applied to the rational design of trusses before the nineteenth century.

Developments in France

It was in France that advanced mathematical and scientific concepts were taught to the new professionals, the *ingénieurs,* at the Ecole des Ponts et Chaussées and the Ecole Polytechnique. Analyses of trusses are contained in Navier's *"Résumé des Leçons Données à L'Ecole des Ponts et Chaussées sur l'Application de la Mécanique"* [4]. The lectures, first published in 1826, include the explicit solution for the forces in a simple triangular truss, called a "king post" truss if a vertical bar is added (see Fig. 1). Navier also determined the forces in simple statically indeterminate trusses, but it was an analogy which Navier made between stresses in beams and the forces in the chords of a truss which perhaps had the greatest influence on the design of early trusses. He noted that a parallel chord truss can be treated as a beam, with a stiffness proportional to the area of the chords multiplied by the square of the distance between them. So for single-span trusses the maximum forces in the chords could be reliably computed from Navier's formulas. Chord areas of American wooden truss bridges in the 1830s and 1840s were sized using Navier's analogy. But France lacked forest resources which made wooden truss bridges natural choices in the United States, and it appears that in France the truss form was initially adopted primarily for roofs.

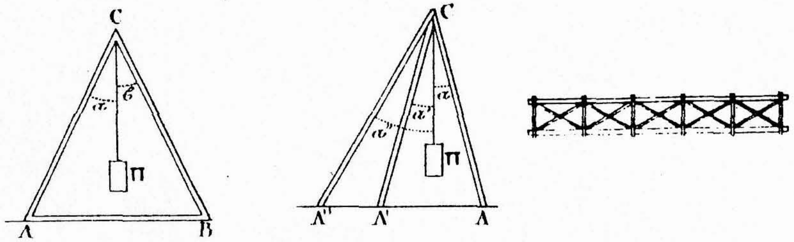


FIG. 1. Trusses analysed by Navier (from *Resumé des Leçons...*, 1826).

Camille Polonceau, an 1833 graduate of the Ecole Centrale des Arts et Manufactures, patented a truss form in 1837 and first used it on roofs for structures built for a railroad from Paris to Versailles [5]. It essentially consisted of two inverted king post trusses tied together (see Fig. 2). Wood or cast iron were used for the compression elements and wrought iron for the bars in tension. For longer spans, three compression members perpendicular to the sloping roof were used. Two noteworthy projects using the Polonceau truss were conceived by the engineer Eugène Flachat. One, cited by Sigfried Giedion in *Space, Time and Architecture,* was a project for the Grandes Halles submitted in 1849 (see Fig. 2). The longest span was a remarkable 260 feet. The roof was designed in such a way that the gravity loads were applied only at the joints so as to eliminate bending stresses in the sloping chord bars. The design indicates an understanding of truss behaviour and the exceptional span strongly suggests that the forces in the bars were calculated. A project actually executed by Flachat was the iron roof for the Gare Montparnasse in Paris, built in 1850–52 using Polonceau trusses on a span of 131 feet. The Polonceau design was also used in Britain; the *Description of Some Roof Trusses Erected at Different Places Within the Last Few Years* written by a Captain Denison in 1843 includes a Polonceau roof truss used for the passenger roof of the Birmingham station of the Birmingham and Derby Junction Railway [6]. (This French Polonceau truss is known in the United States as Fink truss, after the German-American engineer Albert Fink (1827–1897), even though the truss was in use both in France and in Britain before Fink graduated from the Darmstadt Polytechnic in 1848.)

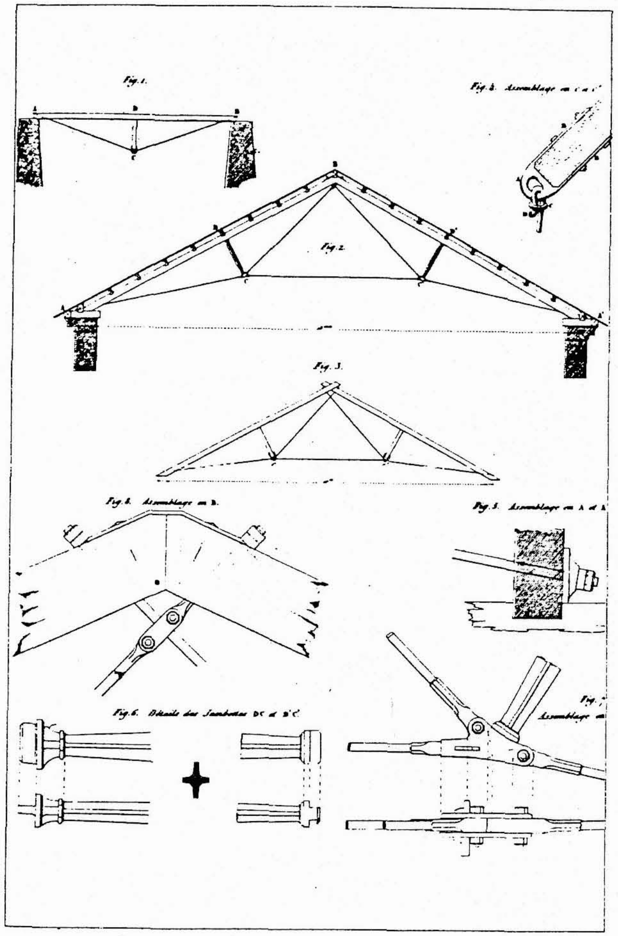


FIG. 2. The Polonceau roof truss.

A measure of the state of the art in the design and analysis of trusses in France by the middle of the nineteenth century is contained in the lectures of the engineer

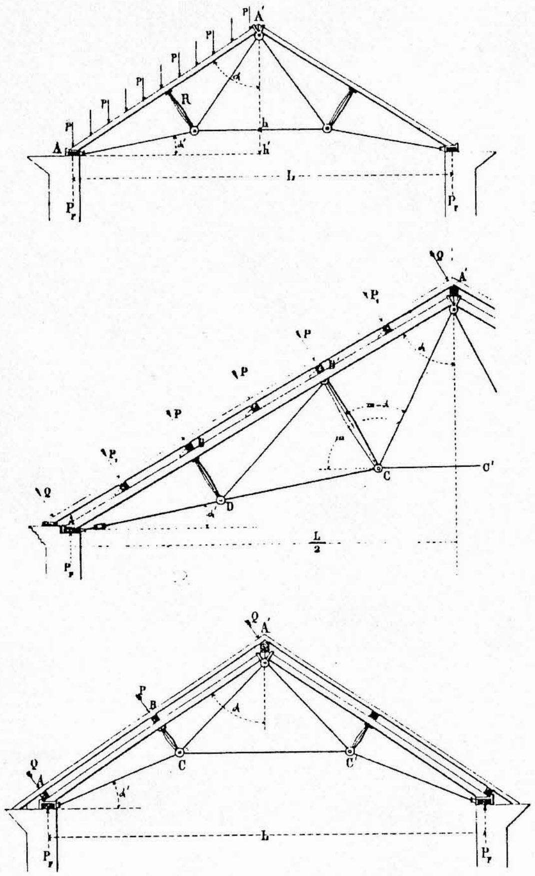


FIG. 3. Polonceau trusses analysed by Michon (from *Instruction sur la Résistance des Materiaux*..., 1848).

Michon, a professor at the military school at Metz. The edition of his lectures published in 1848 [7] contains general analytical formulas for the forces in the bars of several roof trusses which are essentially versions of Polonceau's design (see Fig. 3). Using force equilibrium, Michon correctly computed the sense and the magnitude of the forces in the bars of Polonceau's basic truss. Michon also estimated the bending in the wooden sloping chord members or *arbateliers* which directly carry the roof; he then discussed whether the bending stresses were significant or could be safely ignored. As an example he determined the cross-sectional area required for a wrought iron tension bar by dividing the force in the bar by an allowable stress of 8 kg/mm^2. Michon's analyses are not flawless however; he did not distinguish between trusses and systems which depend on bending stiffness to carry the load. Moreover he did not analyse the full Polonceau truss with four panels along the sloping chord, perhaps because of the rather complicated geometry involved.

Developments in Britain

No institutions like the Ecole des Ponts et Chaussées or the Ecole Polytechnique existed in Britain in the early nineteenth century. British engineers were trained through a pupillage system augmented by professional associations such as the Institution of Civil Engineers, founded in 1818. Yet it was in Britain that the first iron bridge was built in 1775–79; it was to Britain that Navier travelled in 1822 to study suspension bridges; and it was in Britain that George Stephenson in 1824 built the first iron railroad bridge, the Gaunless viaduct [8]. The British experience indicates that successful and innovative engineering designs can depend on advanced material technology, careful experimental observation and on personal conviction and strength. Nonetheless the role of mathematical analyses in design was increasing; George Stephenson and Marc Isambard Brunel carefully educated their sons Robert Stephenson and Isambard Kingdom Brunel, both of whom attended schools to the age of seventeen and then continued their education within the pupillage system.

In Britain as in France the truss form was adopted first for roofs rather than for bridges. Robert Stephenson, as chief engineer for the London–Birmingham Railway, used iron roof trusses for the train sheds at the two terminals of the railroad, Euston Square in London and Curzon Street in Birmingham. The trusses, completed by 1839, had spans of 40 feet and 57 feet [9]. The use of round sections for the bars in tension and T-sections for the bars in compression indicates that the designers understood the sense of the forces in the elements, although the exact design methods used remain unknown. The non-combustible nature of iron made it a logical material for railroad train sheds but, more importantly, its use was possible because by 1837 Eaton Hodgkinson and William Fairbairn had completed a pioneering study on the strength of cast iron. A surviving example of British roof truss designs of the period is Robert Stephenson's locomotive roundhouse at Chalk Farm, designed for the London–Birmingham Railway. The structure is 160 feet in diameter with interior columns on a concentric 80 feet diameter circle. Radial iron roof trusses span from the exterior wall to the interior columns.

Robert Stephenon did not utilize parallel-chord trusses for his iron railway bridges; rather he conceived a competing structural form. In close collaboration with Eaton Hodgkinson (who performed the mathematical analyses) and William Fairbairn (who carried out experiments and devised fabrication details) [10], Stephenson designed and built rectangular tube bridges using iron plates. Fairbairn and Stephenson were granted a patent for their 'box' girders in October 1846.

The first parallel-chord trusses used for railway bridges in Britain in the 1840s were iron versions of the lattice truss patented by Ithiel Town in 1820 (see Fig. 4). The chords of such trusses were probably designed using Navier's analogy of the truss as a beam. William Doyne stated in 1851 that he had built a lattice truss for a railway and remarked that "comparing this with a box girder, the sectional area of the top and bottom must be identical in either case" [11]. Because lattice trusses are statically indeterminate, the actual forces in the lattice bars could not be found using solely equilibrium equations. Nonetheless Doyne stated that for his bridge, "The lattice bars

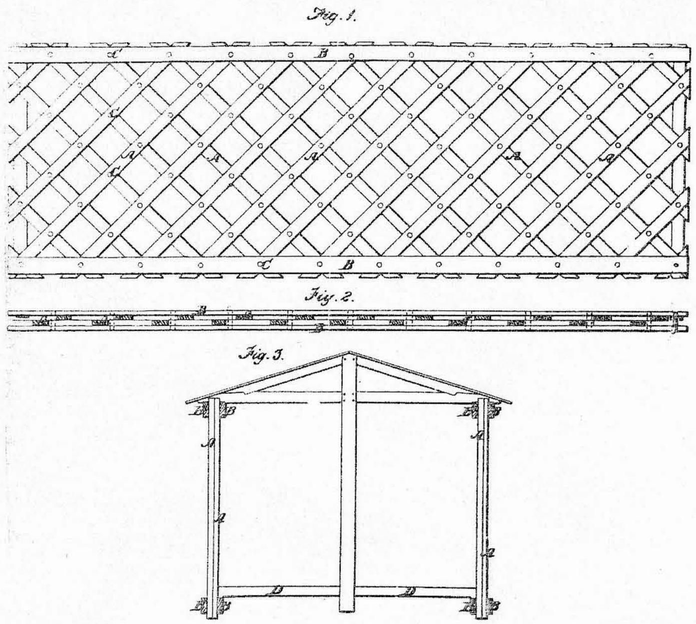


FIG. 4. Ithiel Town's 1820 patent for a lattice bridge (US Patent Office).

were made of plain flat rolled iron 3 inches by $\frac{1}{2}$ inch for 14 feet in the centre and 4 inches by $\frac{1}{2}$ inch for 14 feet at each end, put together with rivets 1 inch in diameter". His statement shows understanding of the fact that, in a uniformly loaded span, the forces in the diagonals increase from the midspan toward the supports.

In 1848 James Warren and Willoughby Theobald Monzani patented a parallel-chord truss with diagonal members alternating in direction; a design whose history was recently clarified by J. G. James in an article in the *Transactions of the Newcomen Society* [12]. James showed that Warren and Monzani's design improved upon a similar truss first patented in France in 1838 by Neville, Nash & Co. of Turin, Italy and then patented by Nash in Britain in 1839. The Warren truss is statically determinate if it is simply supported on a single span. The procedures for determining forces in the bars of a Warren truss were precisely described by William Doyne and William Blood in their paper 'An investigation of the strains upon the diagonals of lattice beams with the resulting formulae' read before the Institution of Civil Engineers on 11 November 1851.

The discussion of the paper highlights two major issues in railway bridge engineering in Britain at mid-century, the relative merits of trusses v. Stephenson's tube girders and the relative merits of lattice trusses v. Warren trusses. Tubular girders were deemed difficult to fabricate and inefficient in their use of materials because of the laps required at joints between plates and because the plates had to be stiffened to prevent instability. Stephenson's tube bridges were, however, torsionally stiff and their dimensions were such that lateral instability was not an issue. Moreover, Stephenson's original idea, to use tubes suspended by chains, was sensible; closed box sections are good systems for decks of suspension bridges. The lattice truss was praised because the lattice bars and the connecting rivets were generally small and so were easily fabricated and erected. William Doyne noted that for the Warren truss "in the case of wide spans, large dimensions of iron must be adopted, the pins would require to be very strong, and the holes must be cut out by expensive machines, instead of by a simple punching press". Isambard Kingdom Brunel pointed out that "it was necessary to draw a distinct line of demarcation between the lattice bridge and that kind of construction called Warren's girder; in the former much of the material employed was useless, whilst in the latter, if properly proportioned, every part was made to perform its duty, either bearing pressure, or in tension". A Warren truss was used for the Newark Dyke Bridge constructed in 1851–53 for the Great Northern Railway. Joseph Cubitt, chief engineer for the railway, described it as follows:

> Each girder consists of a top tube, or strut of cast iron, and a bottom tie of wrought-iron links, connected together by alternate diagonal struts and ties of cast and wrought iron respectively, dividing the whole length into a series of equilateral triangles, of 18 ft 6 inches length of side.... The top tube increases in diameter from 1 foot $1\frac{1}{2}$ inch at the ends to 1 foot 6 inches at the centre; the thickness of the metal also increases from $1\frac{1}{2}$ inch at the ends to $2^5/_8$ inches at the centre.... The lower tie consists of wrought-iron links 18 feet 6 inches in length from centre to centre of the holes, each link being rolled in one piece without any welding. They are of the uniform width of 9 inches, but vary in number and thickness according to the strains to which each length, or portion of the tie, is subject.... The diagonal links are of precisely the same form and dimensions as those of the horizontal tie; and are, in like manner, adapted to the strains to which they are subject, by varying their number and thickness.... The trusses are so arranged, that all compressive strains are taken by the cast iron, and all tensile strains by the wrought iron; the strains, in all cases, in the direction of the length are of the respective parts [*sic*] and all cross strains is avoided. The parts are so proportioned, that when loaded with a weight equal to one ton per foot run, which considerably exceeds the weight of a train of the heaviest locomotive engines in use on the Great Northern, or on any narrow-gauge line, no tensile or comprehensive strain on any part, exceeds five tons per square inch of section. [13]

This leaves no doubt that the size of the bars was based on an analysis of the forces in the various parts of the bridge, an analysis for which Cubitt credits the engineer Charles H. Wild. As with Doyne and Blood's 1851 paper, the discussion of the Newark Dyke Bridge design focused on the relative merits of the Warren truss v. tube girders, with Robert Stephenson and Eaton Hodgkinson taking predictable positions. A genuine concern was that the connections "were a matter for further investigation and experiment" even though the full-scale bridge was load-tested before being placed in service. Another issue was that with the Warren truss "the failure of one piece would hazard the destruction of the whole bridge"—a characteristic of statically determinate structures apparently understood by engineers of the period.

By the middle of the nineteenth century, then, rational iron roof trusses were in use in Britain, even though the actual design procedures involved remain unknown. Parallel-chord lattice trusses and Warren trusses were used for railway bridges; their design was based largely on Navier's analogy with beam behavior until the analyses of the Warren truss by W. Doyne, W. Blood and C. H. Wild. Rankine's and Maxwell's contributions to the theory of trusses were yet to appear.

Developments in the United States

It was in the United States, with its forest wealth and transportation needs, that the art of constructing wooden truss bridges blossomed. The covered wooden truss bridge is now an American romantic icon but in the nineteenth century it was an object of intense technological development [14]. Timothy Palmer (1715–1821), Lewis Wernwag (1769–1843), Theodore Burr (1771–1822), Ithiel Town (1784–1844) and others promoted their bridges and sought commissions for construction. The work of these early builders is recorded in *American Wooden Bridges* [15]. Town's lattice truss patent of 1820 (see Fig. 4) was especially influential, perhaps because of his intense marketing and because the structure did not combine arch and truss action as in Burr's and Wernwag's designs. Although the design procedures used by these early builders remain unclear, it appears that their achievements belong in the pre-scientific period of bridge design.

The first United States builder of wooden truss bridges who published extensively on his design and construction methods was the engineer-explorer Stephen Harriman Long (1784–1864). Long graduated from Dartmouth College in 1809 and taught mathematics at West Point from 1815–16. In 1816 he was appointed Brevet Major in the Topographical Engineers and in 1819 he was charged with "exploring the country between the Mississippi and the Rocky Mountains" [16]. Long journeyed along the Platte and South Platte Rivers and reached the Rocky Mountains in July 1820; although his expedition was only partially successful, and his report controversial, Long did produce a useful map of the territory and Long's Peak in the Rocky Mountain National Park still honours his name. In 1827 Long was appointed engineer for the Baltimore and Ohio Railroad and, with Jonathan Knight, helped to define its routes. In August 1829 he built a wooden truss bridge on the Washington Road, about two miles outside Baltimore. He named the structure the Jackson Bridge, in honour of President Andrew Jackson, and received a patent for it in March 1830 (see Fig. 5) [17].

The bridge was entirely of white pine, except for some iron connectors. The form of the truss was essentially the same as that discussed in Navier's *Leçons*, so Long's patent claims rested on the methods of joining the members. Writing in the *Journal of the Franklin Institute* in 1830, Long referred to the "parallelogram of forces" to explain the equilibrium of forces at the intersection of the primary diagonal brace with the vertical post and the horizontal chord members [18]. He correctly noted that the vertical post is in tension and that the primary diagonal brace is in compression. One of the important patent claims made by Long was for a system of "counterbraces". Normally such braces would act in tension and so would require tension connections, but Long prestressed them in compression by using wedges. Thus, with no loads applied on the bridge, both diagonals were in compression while both chords and the vertical posts were in tension. An advantage of the prestressing was that when loads were applied, both diagonals contributed to the vertical stiffness of the bridge without the need to design a tension connection for either diagonal. Importantly, the precompression also allowed for some shrinkage of the wood without concomitant loosening. Long boasted: "The whole of the timber, except the keys, is white pine, with no other seasoning than what it might have acquired in six or eight weeks, during which time the work was in progress, having been framed and raised in that time by six men only". Long's truss design was well accepted. By 1832 three Long trusses, two of 70 feet span and one of 100 feet span, were built for the Baltimore and Susquehanna Railroad; they were probably the first wooden truss bridges in the US designed to carry railroad loads. In January 1835 Thomas Hassard, one of the "special agents" for Long's patent, stated that he had built 19 Long bridges, including several for the Boston and Worcester and the Boston and Providence Railroads.

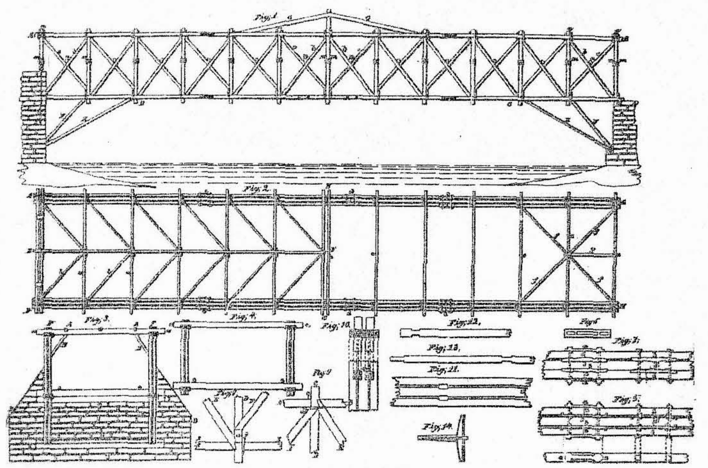
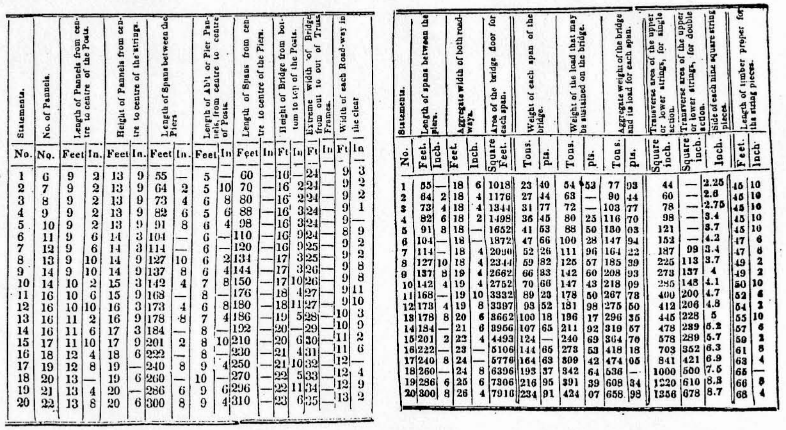


FIG. 5. Stephen Harriman Long's Jackson Bridge patent, 1830 (US Patent Office).

In 1836 Long published a *Description of Col. Long's bridges together with a series of directions to bridge builders* [19]. This contained remarkable tables which stated the depth of trusses and the cross-sectional area of all members for a set of 20 spans ranging from 55 feet to 300 feet (see Fig. 6). The tables were made for "white pine timber: the specific gravity of which is supposed to be about equal to one-half that of water; and its strength such, that a square inch will sustain, (whether by thrust or tension) without permanent alteration, 4,000 pounds". The areas of the chords are consistent with Navier's analysis of a truss as a "framed beam"; Long clearly understood and applied Navier's *Leçons*. Long's trusses were scientifically designed, at least insofar as the chords are concerned. Long also understood the need for bracing to prevent lateral instability of compressive chords. In January 1836 he received a patent for "certain improvements in the construction of wooden or frame bridges", explaining that "*lateral* and *horizontal* stiffness, in contradistinction to *vertical* and *transverse* inflexibility, is the object of this invention."

In November 1839 Long received a US patent for a truss which, at first glance, looks the same as that patented by him in 1830; in reality the new patent showed Long's understanding of the structural behaviour of trusses and of prestressing [20]. Long simply modified his method of prestressing, using wedges on the vertical posts rather than on the diagonals. He was thus able to prestress both diagonals in tension



Statements.	No. of Pannels.	Length of Pannels from centre to centre of the Posts.		Height of Pannels from centre to centre of the strings.		Length of Spans between the Piers		Length of Ab't or Pier Pannels, from centre to centre of Posts		Length of Spans from centre to centre of the Piers.		Height of Bridge from bottom to top of the Posts.		Extreme width of Bridge from out to out of Truss Frames.		Width of each Road-way in the clear	
No.	No.	Feet	In.	Feet	In.	Feet	In.	Feet	In	Feet	In	Ft	In	Ft	In	Ft	In
1	6	9	2	13	9	55	—	5	—	60	—	16	—	24	—	9	3
2	7	9	2	13	9	64	2	5	10	70	—	16	2	24	—	9	2
3	8	9	2	13	9	73	4	6	8	80	—	16	2	24	—	9	2
4	9	9	2	13	9	82	6	5	6	88	—	16	3	24	—	9	1
5	10	9	2	13	9	91	8	6	4	98	—	16	3	24	—	9	—
6	11	9	6	14	3	104	—	6	—	110	—	16	9	24	—	8	9
7	12	9	6	14	3	114	—	6	—	120	—	16	9	25	—	9	2
8	13	9	10	14	9	127	10	6	2	134	—	17	3	25	—	9	2
9	14	9	10	14	9	137	8	6	4	144	—	17	3	26	—	9	8
10	14	10	2	15	3	142	4	7	8	150	—	17	10	26	—	9	8
11	16	10	6	15	9	168	—	8	—	176	—	18	4	27	—	9	11
12	16	10	10	16	3	173	4	6	8	180	—	18	11	27	—	9	10
13	16	11	2	16	9	178	8	7	4	186	—	19	5	28	—	10	3
14	16	11	6	17	3	184	—	8	—	192	—	20	—	29	—	10	9
15	17	11	10	17	9	201	2	8	10	210	—	20	6	30	—	11	2
16	18	12	4	18	6	222	—	8	—	230	—	21	4	31	—	11	6
17	19	12	8	19	—	240	8	9	4	250	—	21	10	32	—	12	—
18	20	13	—	19	6	260	—	10	—	270	—	22	5	33	—	12	4
19	21	13	4	20	—	286	6	9	6	296	—	22	11	34	—	12	9
20	22	13	8	20	6	300	8	9	4	310	—	23	6	35	—	13	2

Statements.	Length of spans between the piers.		Aggregate width of both roadways.		Area of the bridge floor for each span.	Weight of each span of the bridge.		Weight of the load that may be sustained on the bridge.		Aggregate weight of the bridge and its load for each span.		Transverse area of the upper or lower strings, for single action.	Transverse area of the upper or lower strings, for double action.	Side of each nine square string pieces.	Length of timber proper for the string pieces.	
No.	Feet.	Inch.	Feet.	Inch.	Square Feet.	Tons.	pts.	Tons.	pts.	Tons.	pts.	Square inch.	Square inch.	Inch.	Feet.	Inch.
1	55	—	18	6	1018	23	40	54	53	77	93	44	—	2.25	45	10
2	64	2	18	4	1176	27	44	63	—	90	44	60	—	2.6	45	10
3	73	4	18	4	1344	31	77	72	—	103	77	78	—	2.75	45	10
4	82	6	18	2	1498	36	45	80	25	116	70	98	—	3.4	45	10
5	91	8	18	—	1652	41	53	88	50	130	03	121	—	3.7	45	10
6	104	—	18	—	1872	47	66	100	28	147	94	152	—	4.2	47	6
7	114	—	18	4	2090	52	26	111	96	164	22	187	09	3.4	47	6
8	127	10	18	4	2344	59	82	125	57	185	39	225	113	3.7	49	2
9	137	8	19	4	2662	66	33	142	60	208	93	273	137	4	49	2
10	142	4	19	4	2752	70	66	147	43	218	09	285	148	4.1	50	10
11	168	—	19	10	3332	89	23	178	50	267	78	400	200	4.7	52	6
12	173	4	19	8	3397	93	52	181	98	275	50	412	206	4.8	54	2
13	178	8	20	6	3662	100	18	196	17	296	35	445	228	5	55	10
14	184	—	21	6	3956	107	65	211	92	319	57	478	239	5.2	57	6
15	201	2	22	4	4493	124	—	240	69	364	70	578	289	5.7	59	2
16	222	—	23	—	5106	144	65	273	53	418	18	703	352	6.3	61	8
17	240	8	24	—	5776	164	63	309	42	474	05	841	421	6.9	63	4
18	260	—	24	8	6396	193	37	342	64	536	—	1000	500	7.5	65	—
19	286	6	25	6	7306	216	95	391	39	608	34	1220	610	8.3	66	8
20	300	8	26	4	7910	234	91	424	07	658	98	1356	678	8.7	68	4

FIG. 6. Tables for the depth of trusses and cross-sectional areas of members by Stephen Harriman Long (from *Description of Col. Long's Bridges . . .*, 1836).

and the posts in compression, presumably with forces large enough so that the sense of the forces did not change when loads were applied on the bridge. Long explained:

> The straining or trussing, of the truss frames is effected by driving the counter wedges, above mentioned, which are situated, as shown in the drawing, between the upper end of each post and the upper string-pieces, but which may, if preferred, be situated between the lower ends of said posts and the lower string pieces. This operation is calculated to elevate the upper string, at the points where the main braces are attached to it; and of course to increase the tension of the main braces of the adjacent panel. Every increment of tension thus produced is counteracted by a corresponding degree of antagonal tension in the counter braces. Hence the main and counter braces act by tension instead of thrust, and the posts by thrust instead of tension.

Long also attempted to equalize the forces in the diagonals by decreasing the distance between the posts from the centre of the span to the supports. Although impractical, Long's idea was structurally correct for a uniform load over the entire span. Long was truly an innovative designer of wooden truss bridges, perhaps the first US engineer who understood and applied to trusses the theoretical work of Navier and advanced prestressing concepts.

Navier's work was further disseminated in the United States by the publication in 1837 of Dennis Hart Mahan's textbook *An Elementary Course of Civil Engineering for the Use of the Cadets of the United States Military Academy* [21]. Mahan was an 1824 West Point graduate who became a professor at the Academy in 1825. In 1826 he was authorized (due, in part, to his acquaintance with Lafayette) to study at the military school at Metz in France. He returned to teach at West Point in 1830. In the introduction of his book he states that "the best counsel that the author could give to every young engineer, is to place in his library every work of science to which M. Navier's name is in any way attached". The mechanics portion of Mahan's text considers many of the same examples and provides the same solutions as those found in Navier's *Leçons*. Specifically, Mahan gives the solution for the forces in a king-post truss and states Navier's analogy regarding parallel-chord trusses as beams.

In the 1840s there was a gradual transition from wood to iron bridges in the United States, accompanied by a blizzard of patents. William Howe (1803–52) replaced the vertical wooden posts on Long's truss with iron rods and received patents for his trusses in 1840 and in 1846 [22, 23]. As with Long on the Jackson Bridge, Howe prestressed the wooden diagonals in compression. But unlike Long, who prestressed by means of wedges on the diagonals, Howe simply tightened the vertical bars, a much simpler process to carry out. Howe's design simplified the connection between the vertical tension bars and the chords; the only wood-to-wood tension connections which remained were in the bottom chord.

In 1844 Caleb and Thomas Pratt patented a truss with iron diagonal bars [24]. If their truss was prestressed by wedges on the vertical posts, or by tensioning the diagonals, then its behaviour was exactly the same as Long's 1839 patent truss. If no prestressing was done, then only one of the diagonals in each panel contributed to the vertical stiffness of the truss. Howe's and Pratt's designs were easier to construct and so were very successful; to this day, structural engineers in the United States use the Howe and Pratt names to identify trusses. From a structural engineering point of view, however, Howe's and Pratt's trusses are based on Long's designs and writings and do not embody any new understanding of truss behaviour.

An important patent for all an all-iron bridge structure was that granted to Squire Whipple in 1841 [25]. Whipple was an 1830 graduate of Union College and began his career as a surveyor on the Baltimore and Ohio Railroad, although there is no evidence of technical collaboration with Long. Whipple used a "bowstring" form with rods for the vertical, diagonal and lower chord members (see Fig. 7). Because the rods can only act in tension, equilibrium cannot be satisfied by purely axial forces for any arbitrary load condition, and so the structure is not a truss but rather a tied arch. Nevertheless, the successful use of Squire Whipple's bridges, especially for roads over the Erie Canal, was a proof test for the usefulness and reliability of iron bridges.

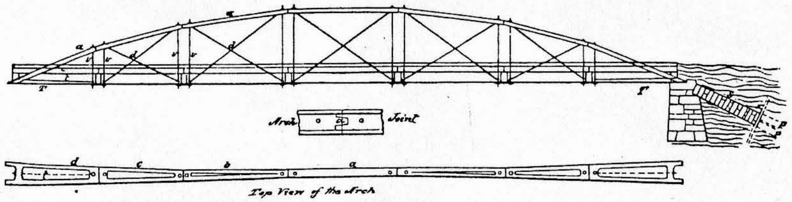


FIG. 7. Squire Whipple's patent for a bowstring iron bridge, 1841 (from C. Condit, *American Building Art in the Nineteenth Century*, 1960).

The honour of having constructed the first all-iron railroad truss in the United States belongs to the engineers of the Philadelphia and Reading Railroad who in 1845 erected a 42 feet long all-iron Howe truss in West Manayunk, near Philadelphia [26, 27]. Other all-iron railroad bridges were patented by Nathaniel Rider in 1845 and Frederick Harbach in 1846; their designs were innovative because of the use of iron but they did not represent new forms nor an advance in the understanding of truss behaviour.

Such an advance occurred in 1847 when Squire Whipple published *An Essay on Bridge Building* [28], in which he correctly explained how to obtain forces in the members of a Long–Howe–Pratt truss. Rather than utilizing their form, however, he patented a design which was essentially a variation of the Pratt truss. In 1848 Whipple constructed for the Erie Railroad a 50 feet bridge which he described as follows:

> The trapezoid had six panels, 8 feet 8 inches depth of truss, upper chord and end braces of cast iron hollow cylinders, 6 inches in diameter and about 5/16 inches thick; end braces cast in two pieces and joined by bolts and flanges. Verticals of the cruciformed section with connecting blocks or pins cast upon the lower ends to receive the chord links upon the ends, and the diagonals through holes in the enlarged central portions. Trusses 8 feet apart with struts and horizontal diagonals between upper chords and end braces. Open chord links of $1\frac{1}{4}$ inches iron (5 sq. inches section to the truss) in the two middle and 1 inch iron in the other panels. Main diagonals in pairs and counters single, and in size from $\frac{3}{4}$ inches to $1\frac{1}{4}$ inches diameter according to their respective liabilities to strain." [29]

Whipple's bridge therefore may have been the first truss in the United States in which all the members' areas were determined from forces obtained by a correct truss analysis.

Summary

By the mid-nineteenth century, rational truss forms were designed and used in France, Britain and in the United States. Those achievements, the additional theoretical developments of Maxwell, Mohr and Castigliano and the development of steel led to the great truss designs of the second half of the nineteenth century. Today, although trusses have fallen out of favour as structural systems for bridges, they remain in wide use. Three prominent examples are New York City's Jacob K. Javits Convention Center, The Bank of China Building in Hong Kong and NASA's structural system for the space station. The latter will truly be a 'space' truss, a remarkable descendant of the prestressed flying box trusses of the biplane era, of American wooden bridges and of the ancient king-post truss.

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References

[1] R. Dorn and R. Mark, 'The Architecture of Christopher Wren', *Scientific American* (July 1981), pp. 160–173.

[2] J. G. James, 'The Evolution of Wooden Bridge Trusses to 1850', *Journal of the Institute of Wood Science*, 9 (June and December 1982), pp. 116–135 and 168–193.

[3] S. P. Timoshenko, *History of Strength of Materials*, (New York, 1983).

[4] C. L. M. H. Navier, *Resumé des Leçons Donnés a L'Ecole des Ponts et Chaussees sur L'Application de la Mécanique a L'Etablissement des Constructions et des Machines* (Second edition, Paris, 1833).

[5] J. B. Ache, *Acier et Architecture* (Paris, 1966), pp. 18–21.

[6] Capt. Denison, 'Description of Some Iron Roofs Erected at Different Places Within the last Few Years', *Royal Engineers Professional Paper*, 6 (1842), plate 49.

[7] Michon, *Instruction sur la Resistance des Materiaux—Suivie d'Applications aux Pièces Droites et aux Fermes de Charpente des Bâtimens* (Metz, 1848).

[8] D. Beckett, *Stephensons' Britain* (North Pomfret, Vermont, 1984), pp. 102–103.

[9] R. Mainstone, *Developments in Structural Form* (Cambridge, MA., 1975), p. 153.

[10] N. Rosenberg and W. Vincenti, *The Britannia Bridge: The Generation and Diffusion of Technological Knowledge* (Cambridge, MA., 1978).

[11] W. T. Doyne and W. B. Blood, 'An Investigation of the Strains Upon the Diagonals of Lattice Beams, with the Resulting Formulae', *ICE Proceedings*, XI (November 1851), pp. 1–15.

[12] J. G. James, 'The Evolution of Iron Bridge Trusses to 1850', *Transactions of the Newcomen Society*, 52 (1980–81), pp. 67–101.

[13] J. Cubitt, 'A Description of the Newark Dyke Bridge on the Great Northern Railway', *ICE Proceedings*, 12 (1853), pp. 601–612.

[14] C. W. Condit, *American Building Art in the Nineteenth Century* (New York, 1960).

[15] Committee on History and Heritage of American Civil Engineering, *American Wooden Bridges* (New York, 1976).

[16] R. G. Wood, *Stephen Harriman Long, 1784–1864: Army Engineer, Explorer, Inventor* (Glendale, CA., 1966).

[17] US Patent granted to S. H. Long, March 6, 1830.

[18] S. H. Long, 'Observations on Wooden, or Frame Bridges', *Journal of the Franklin Institute*, X, pp. 252–255.

[19] S. H. Long, *Description of Col. Long's Bridges Together with a Series of Directions to Bridge Builders* (Concord, NH, 1836).

[20] US Patent No. 1397 granted to S. H. Long, November 1839.

[21] D. H. Mahan, *An Elementary Course of Civil Engineering for the Use of the Cadets of the USMA* (New York, 1837).

[22] US Patent no. 1711 granted to William Howe, August 1840.

[23] US Patent no. 4726 granted to William Howe, August 1846.

[24] US Patent no. 3523 granted to Caleb and Thomas Pratt, April 1844.

[25] US Patent no. 2064 issued to Squire Whipple, April 1841.

[26] H. G. Tyrell, *History of Bridge Engineering* (Chicago, Illinois, 1911).

[27] E. L. Kemp and R. K. Anderson, Jr., 'The Reading-Halls Station Bridge', *IA, The Journal of the Society for Industrial Archeology*, 13 no. 1 (1987), pp. 17–40.

[28] S. Whipple, *A Work on Bridge Building, Consisting of Two Essays, the One Elementary and General, the Other Giving Original Plans, and Practical Details for Iron and Wooden Bridges* (Utica, New York, 1847).

[29] S. Whipple, 'The Development of the Iron Bridge', *The Railroad Gazette* (April 19, 1889), pp. 253–254.