The Crystal Palace and its Place in Structural History

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The Crystal Palace and its Place in Structural History

Bill Addis

ABSTRACT: Completed in 1851 to house the Exhibition of All Nations in London, the Crystal Palace was the first large public building that departed completely from traditional construction materials and methods. It was the first major building to be conceived by its design engineers, William Barlow and Charles Fox, as a rigid-jointed iron frame and one of the earliest to use horizontal and vertical cross-bracing to carry wind loads. Working closely with the contractor John Henderson, the designers also applied their knowledge of modern production engineering methods to ensure the building was constructed in the incredibly short time of 190 days. Within twenty years the iron frame, supporting thin walls of masonry, would become established as a viable alternative to load-bearing masonry walls for large buildings.

1. INTRODUCTION

The Crystal Palace is one of the best-known icons of nineteenth century architecture and often hailed as the building that initiated the move away from traditional construction materials and methods, opening the way in Europe to the Modern Movement and, in the USA, to the growth of high-rise building. In Britain, ironically, the half century following the Crystal Palace was dominated by the Gothic Revival and the Arts and Crafts movement which looked back to old traditions rather than forward to a new age. One reason why the building has become so famous is the enormous publicity it received at the time [1, 2, 3, 4, 5] and this has made good modern historical studies relatively easy to produce [6, 7, 8, 9, 10, 11, 12, 13].

While sometimes claimed to be an invention that appeared from nowhere, so to speak, perhaps the most remarkable feature of the Crystal Palace was that it was constructed using tried and tested materials, construction methods and building design ideas. The great innovation, that was essential to meet the short time available for construction, was bringing more than half a century's collected experience in various fields of building construction and manufacturing engineering together in a single building. As I. K. Brunel (see Appendix) observed in February 1850, still more than five months before a suitable design would be chosen, yet only 15 months before the exhibition was to open, the need for "skill of construction, economy of construction and design, and rapidity of construction would call forth all those resources for which England is so distinguished".

2. THE DESIGN COMPETITION

The idea of holding an "exhibition of all nations" was proposed in 1849 by Queen Victoria's husband, Prince Albert. The Royal Commission formed to oversee the project announced that the building would need to have a target net area of 800,000 square feet and the upper limit for the contract was set at £100,000. Not only would this be the largest building ever constructed, it would also have to be cheaper, per cubic foot, than any building previously built. A design competition was launched on 13th March 1850 with a deadline of 8th April. On 17th March, it was decided that the exhibition would be opened by Queen Victoria herself on 1st May 1851, just 13 months hence. The competition required that the scheme should indicate how the predicted exhibition areas would be laid out and how people would be able to access them. The structure had to be fire-proof. The building would need to be removed after the end of the exhibition leaving the site, with its many large trees, re-instated. The competition attracted 245 entries but the Building Committee judged them all to be unsuitable, and set about preparing its own design. When this was made public at the end of May, it attracted widespread criticism and the members of the Royal Commission must have wondered how they were going to fulfil their task.

This was the context in which Joseph Paxton began to take a serious interest in the project. He was the manager of the Duke of Devonshire's large estates at Chatsworth, near Derby in the English Midlands. He was also a director of the London Midland Railway (LMR) whose headquarters were at Derby. As the landscape gardener for the estate, he had commissioned several glass houses more than a decade earlier and he realised that this form of construction could be built very quickly and its repetitive, modular form could be extended at will to cover the enormous area needed for the exhibition.

Paxton made his famous blotting paper sketch during a meeting of the LMR directors on Tuesday, 11th June. [Fig.01] To develop his initial idea, he called upon the assistance of one of the LMR's building engineers, William Barlow (see Appendix). The two of them worked almost day and night for the following week and produced a set of drawings of the scheme that differed in only one significant way from the building that was built (it lacked the vaulted transept). [Fig.02] On Thursday, 20th June, Paxton took their drawings to London. By chance he met Robert Stephenson, a member of the Building Committee (see Appendix) at Derby Station and during their journey together, Stephenson cast his expert eye over the Paxton / Barlow scheme, and pronounced it excellent.

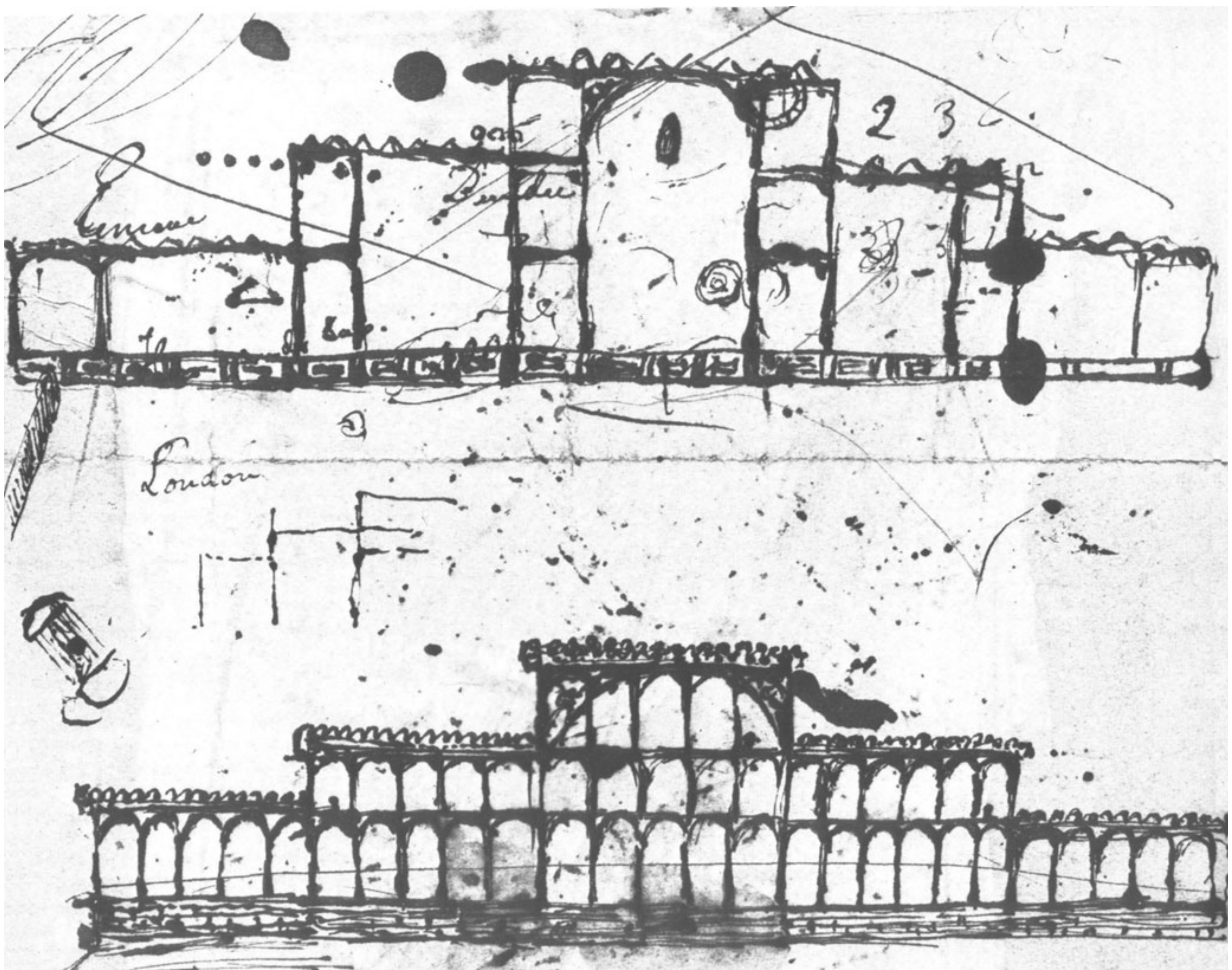


Figure 1. Paxton's first blotting-paper sketch for the Crystal Palace.

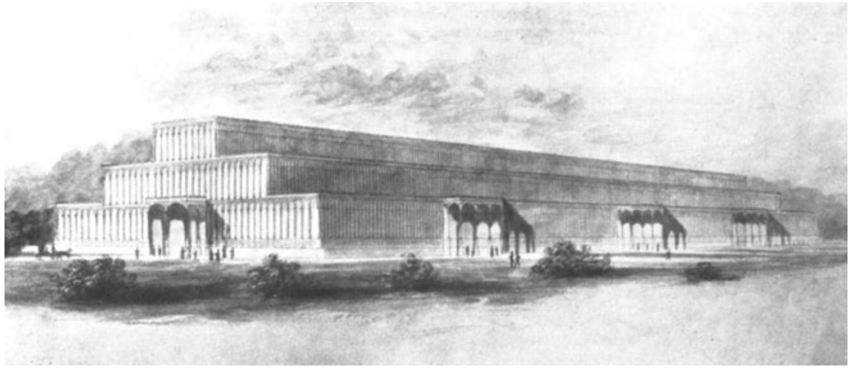


Figure 2. The Paxton-Barlow scheme published in the Illustrated London News.
Source: Illustrated London News (ILN)

On the following day Paxton contacted the contracting firm of Fox Henderson, which he knew from their work on the LMR, and the glass makers Chance Brothers whom Paxton had used for his Great Conservatory. Charles Fox, John Henderson (see Appendix) and a representative of the firm Chance Brothers met in London on Monday 23rd June and several times later that week in Smethwick and Chatsworth. By the end of the week the design, construction method and logistics were developed sufficiently to prepare their cost estimates, and the three parties signed an agreement on 29th June to work together should their scheme be selected by the Building committee.

Despite Stephenson's recommendation, the Building Committee was not enthusiastic about the Paxton / Barlow scheme; to have supported it would have been to admit the failure of their own design. At this point, Paxton played a master stroke – he got their scheme published in the Illustrated London News on Saturday, 6th July. The public reaction was immediate and favourable. Although, technically, other options were still to be considered, the outcome had, in effect, already been decided.

Contrary to Paxton's wishes, Henderson added a transept with a flat roof in order to provide better lateral stability to the building. On 11th July, the Building Committee considered the schemes and tenders that had been submitted. Of the Paxton design, they required that the transept must be tall enough to enclose the three large elm trees which were some 20 feet higher than the roof currently proposed. Paxton then had the idea of using the laminated timber arch system he had developed for his Great Conservatory more than ten years previously. This was both practical and of great visual significance, for the huge barrel vault that formed this transept was the one feature that offered relief from the monotony of the repeating bays, and provided a degree of architectural interest.

The Building Committee finally gave its blessing to the scheme on 15th July and the Royal Commission endorsed this decision on Friday, 26th July. A fixed-price tender from Fox Henderson was accepted, with a completion date for the building on 31st December, just twenty two weeks hence. The contractors started on site on Tuesday 30th July.

3. THE DESIGN OF THE CRYSTAL PALACE

3.1 The structural frame and gallery floors

The building was basically rectangular in plan, with some minor single storey additions along the south front. [Fig.03] At ground floor level it was laid out as 77 × 17 bays, with columns at 24 feet centres. The overall length of the building, depending on how you measure it, was between 1849 feet 6 inches and 1850 feet 3 inches, and a few inches more on a hot day (1 foot = 12 inches = 305 mm). The second tier of the building was 11 bays wide and the third tier, just 5 bays. The arched transept had a rectangular plan, 17 × 11 bays, and both the 'nave' and the transept were 3 bays wide, forming a square, on plan, at the crossing. The 1309 bays at ground floor level provided an area

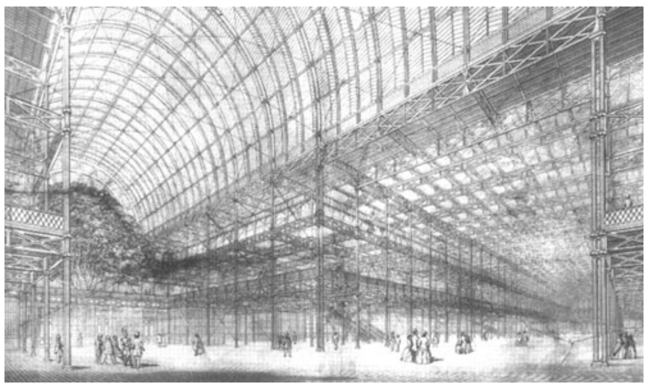


Figure 3. Interior perspective of Crystal Palace.
Engraving by R.P Cuff.

of some 17.3 acres (70,000 square metres) for exhibition use. To this was added an additional area of 3.8 acres in the form of first floor galleries covering about a quarter of the ground floor area (381 bays, with a further 20 bays needed for staircases). The remaining volume of the building was void up to roof level.

The entire structure of the building was formed using cast iron columns in just two lengths – ground floor columns were 22 feet long, those above, 20 feet. Girders 3 feet deep spanned between the columns at 24, 48 or 72 feet centres. The tension members of the 48 and 72 foot girders were made of wrought iron and their compression elements of cast iron, and were assembled on site, at ground level, using rivets. The 24 foot girders were single units of cast iron (apart from a few that were damaged in transit and replaced by girders similar to the 48 foot girders, built on site).

All the columns and girders were designed precisely to carry the loads they were expected to carry, yet in all cases the external dimensions were kept constant in order that they would fit within the same 24-foot modular dimension and fit the standard connectors. In the girders this meant using flat iron bar of a size to suit the loads. For the columns, the cross-section of the columns was increased as needed by increasing the wall thickness and reducing the diameter of the internal hole that served also as the drainpipe. Some twenty different column sizes were used in various different locations.

The ground floor columns were bolted to column bases which rested on concrete pad foundations. The hollow columns acted as drain pipes for rainwater falling on the roof and the bases incorporated connections for the longitudinal drains that carried the rain water eastwards to the three main drains which ran transversely, north-south carrying the water into the main sewer to the south of the building. [Fig.04]

The girders and columns were held together by an ingenious connection that relied only on wedges to provide a rigid connection. [Fig.05] [Fig.06] The wedges were of cast iron in the direction perpendicular to the nave and of oak along its length, except for the three bays at each end and on either side of the transept. The oak provided some possibility of longitudinal movement as the building expanded and contracted with changes in temperature.

The floors of the galleries were supported using a two-way spanning system of trussed beams, with additional binders and rafters to ensure that the floor load was distributed to the four perimeter girders. [Fig.07]

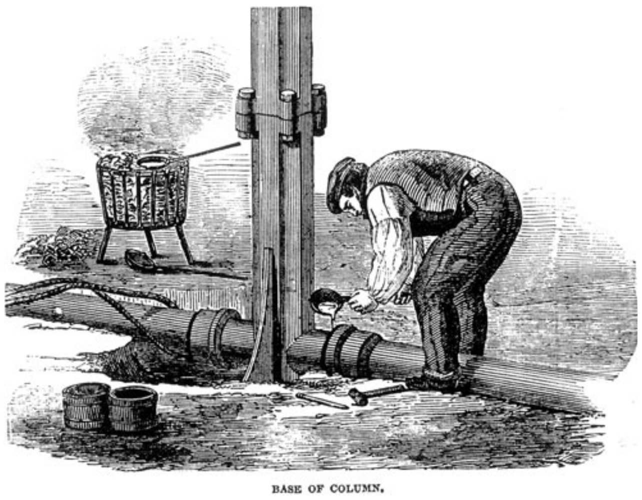


Figure 4. Cast-iron column base, fixed to a concrete foundation, being connected to horizontal section of drain pipe using molten lead. (ILN).

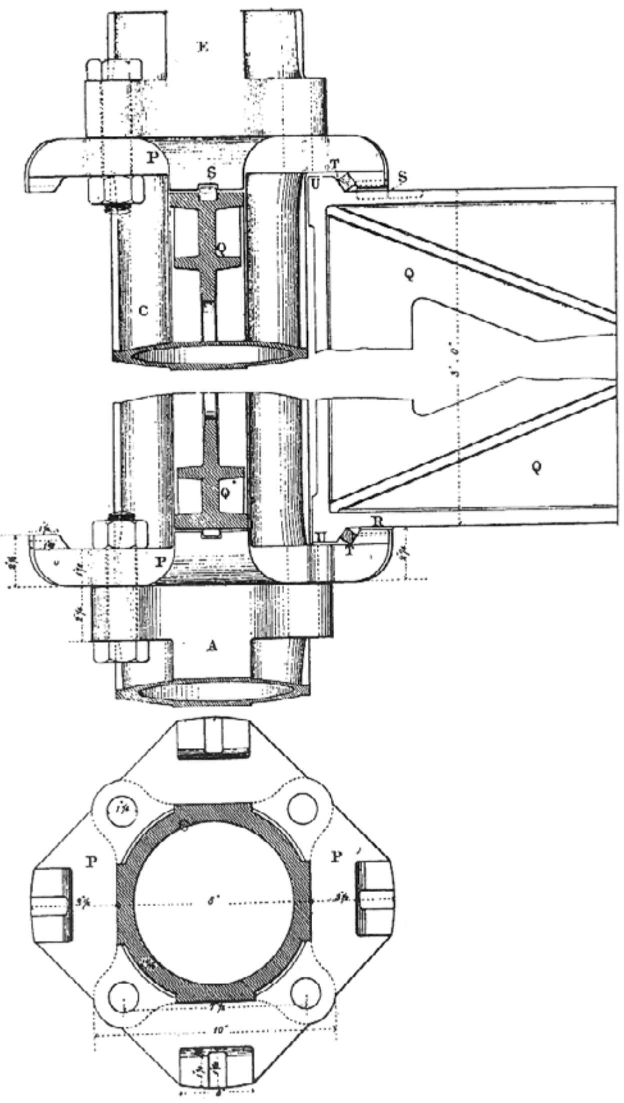


Figure 5. Section of the connection between column and girders showing positions of wedges of iron and oak (Downes 1851).

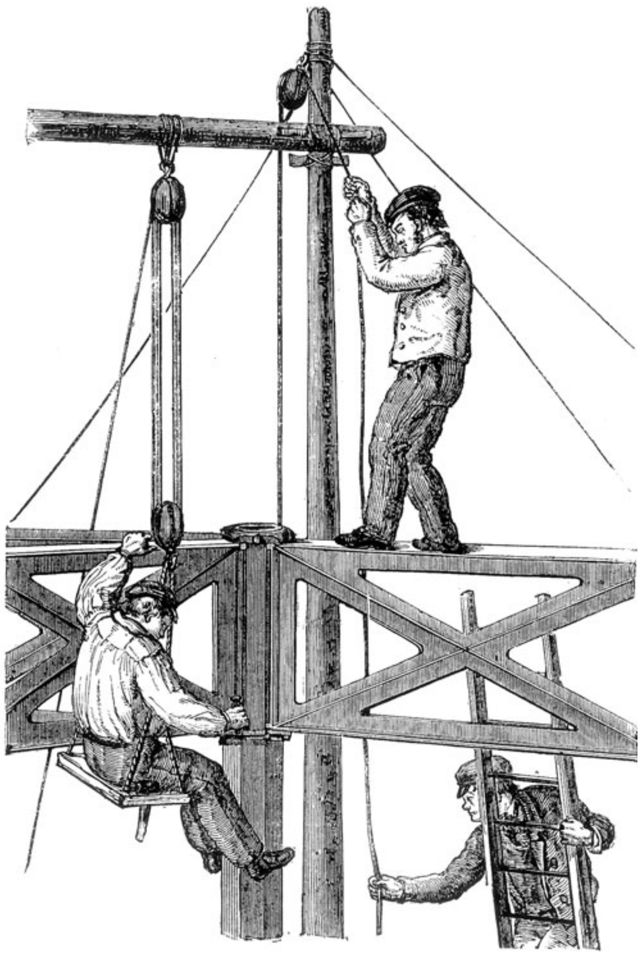


Figure 6. A connection between column and girder being fixed (ILN).

3.2 The transept arches

The sixteen arched ribs spanning over the transept were made of timber and wrought iron. While these arches are usually said to be made of "laminated timber", this term is misleading in view of what we mean today by the term, i.e. a series of thin planks built up and bonded by waterproof adhesive to form a large structural section. Each rib was made from arcs of flat timber planking each 9'6" long, built up in three vertical layers – two 2" wide by 13.5" deep either side of one 4" by 13.5" deep. [Fig.08] The three layers were bolted at 4-foot intervals. To the intrados of this arc was fixed a timber moulding to match the external profile of the columns, and an iron strip; to the extrados was fixed a gutterboard and a second iron strip. The composite section was bolted radially through the depth of the rib at 2-foot intervals.

3.3 The glazed building envelope

The roof over each bay comprised three spans of ridge-and-furrow glazing supported on the ingenious 'Paxton gutter' which carried both rainwater from outside, and condensation from the interior surface of the glass along separate channels to transverse timber channels and thus into the top of the hollow columns. [Fig.09] The strength of the gutter was achieved using adjustable trussing rods which were tightened to pre-camber the gutters and hence prevent the inevitable ponding that would otherwise have resulted from their deflection under load.

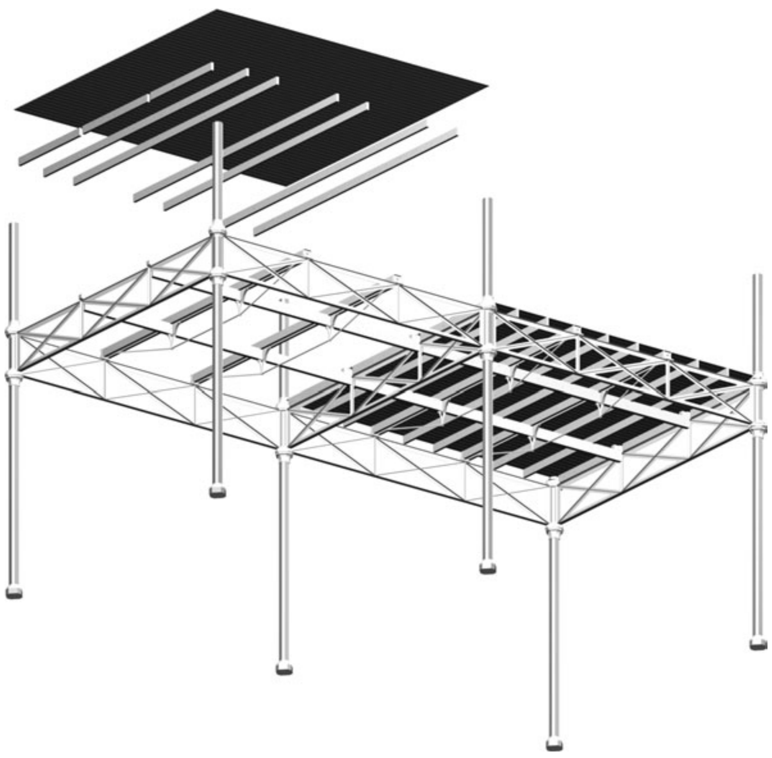


Figure 7. Exploded isometric of the gallery floor structure (3D model – Neil Hamill).

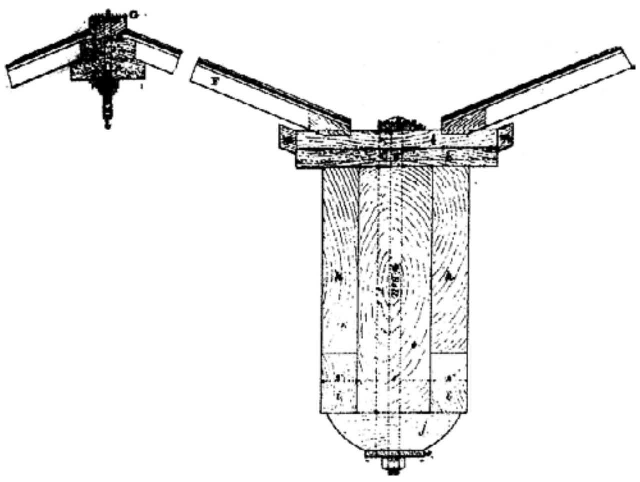


Figure 8. Cross section of the laminated timber arch rib of the transept vault (Downes 1851).

In the vertical façade of the building, each 24 foot Bay was divided into three by two timber sashes which resembled the cast-iron structural columns. The panels of the façade were either glazed or of timber planking.

The façade also incorporated the louvres which provided natural ventilation when needed. These were installed at the top of each of the 1580 or so panels in the entire façade. At ground level, louvres were also fitted at the foot of about half of the panels. Curved galvanised iron blades of the louvres were mechanically coupled in gangs of five and driven by a rope and pulley mechanism that could be operated manually from ground or gallery level.

To reduce the considerable solar gain, an external covering of "buff calico" covered the entire flat portion of the roof, and over the glazed parts of the long south-facing façade. The roof of the transept was left uncovered.

3.4 The stability of the building

The stability of the structural frame and its ability to carry wind loads from the façade to the foundations was achieved in two ways. The first was through frame, portal or Vierendeel action made possible by the rigidity of the connections between columns and girders [Fig.13]. This technique was rare at the time and to explain how it worked, Paxton, Fox and others likened the system to that used in a wooden table. Indeed, they even extended the metaphor by likening the ridge-and-furrow glazing to the table cloth.

The second stability system was the diagonal-bracing fitted in 220 vertical bays. [Fig.03]. This had not been included in the early scheme designs but was added at some stage during the detailed design, partly in light of the nervousness of using cast iron to carry bending following a number of collapses of factory buildings with cast-iron beams and columns. The timber floors of the galleries comprised 1.25 inch boards with one-inch iron tongues and provided considerable lateral stability to the structural frame, helping carry the horizontal wind loads from the

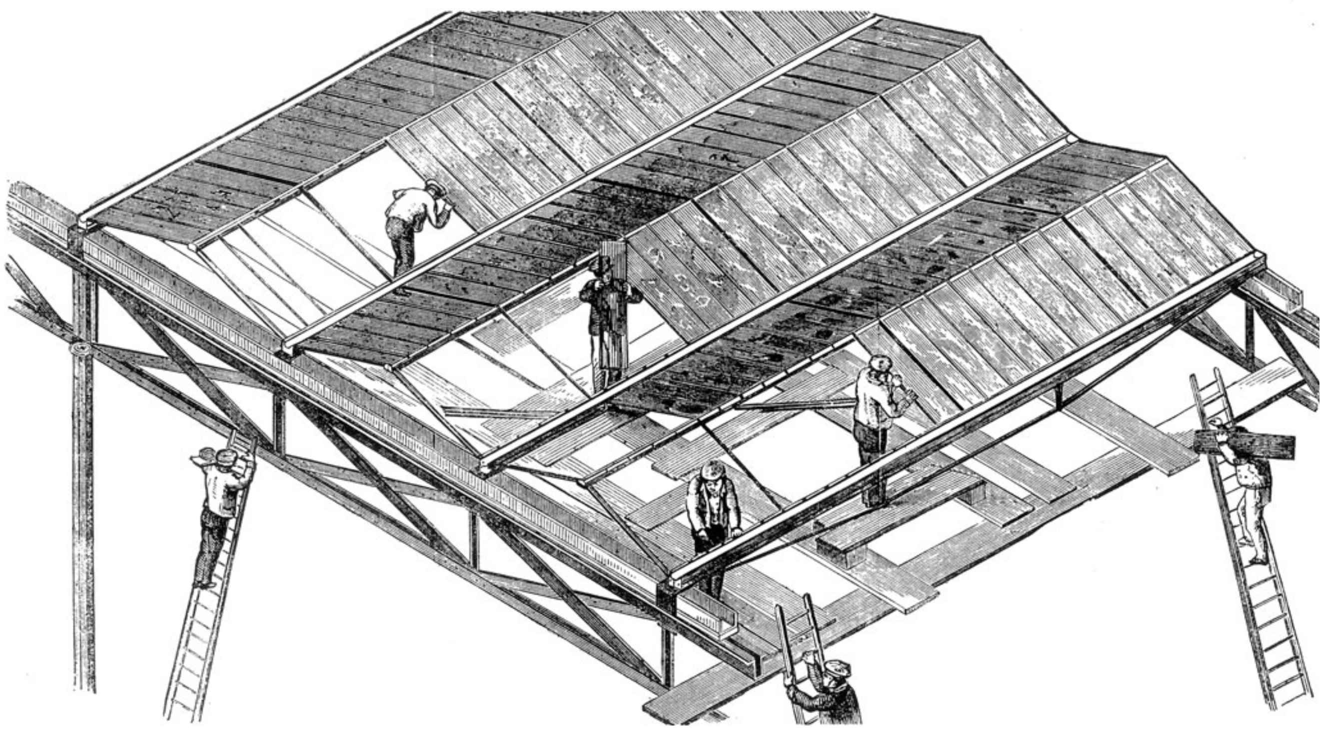


Figure 9. The Paxton ridge-and-furrow roofing system (ILN).

façades to the vertical diagonal bracing and down to the ground.

Flanking the arch of the transept was the only area of roof not covered with Paxton glazing. It was called the flat lead roof. This flat roof was constructed similar to the galleries with the addition of *horizontal* diagonal bracing in some of the bays. In addition, 22 sets of horizontal cross-bracing were used to brace the large façades at each end of the building and of the transept. [Fig.10]

3.5 Concerns about structural safety

One important issue came up again and again during the project – during design, construction and after the building's completion, before its opening to the public. This was the safety of the galleries. The cause for concern was the reputation that cast iron had been gathering during the 1840s as a material that was not safe. Cast iron is weak in tension – about one-sixth of its strength in compression; more significantly, it is also brittle, meaning that a failure can happen without any warning and is catastrophic.

In 1850 the terrible consequences of structural collapse were fresh in the minds of engineers, journalists and the public alike. In 1844 a new extension to a mill in Oldham, with cast-iron columns and beams, had collapsed suddenly during construction due to the fracture of a cast-iron beam and the consequent progressive collapse of the entire building. Twenty people were killed and many more injured. A Royal Commission set up to identify the causes of the accident concluded that the relative weakness and the brittle nature of cast iron had been the cause of the terrifying progressive collapse and recommended that wrought iron should be used in place of cast iron for load-bearing elements of all types of building.

The inquiry also identified the contribution made by dynamic loads – percussive loads from vibrating weaving machinery at Oldham. It did not, however, find a satisfactory explanation linking dynamic loads to the unexpected fracture of cast iron components. (Metal fatigue was first identified as a cause of such fractures in the late 1850s). In 1850, then, feelings about using cast iron, especially in public structures, were pervaded by mystery and uncertainty.

The concern at Crystal Palace was, quite rightly, that people induce dynamic loads which might lead to consequences as serious as at Oldham. The construction team went to great lengths to put the public at ease. Each of the 24-foot cast-iron girders that would support the gallery floor was tested under static load to 15 tons, twice what it was expected to carry, using a hydraulic test rig. [Fig.11] Dynamic load-testing of a test bay of the gallery floor was undertaken, first by construction workers and then by soldiers. [Fig.12] As Wyatt reported:

> *'no action of walking, running or jumping of three hundred men did any injury to it. Soldiers, of the corps of Royal Sappers and Miners, were then substituted for the contractors' men, and although*

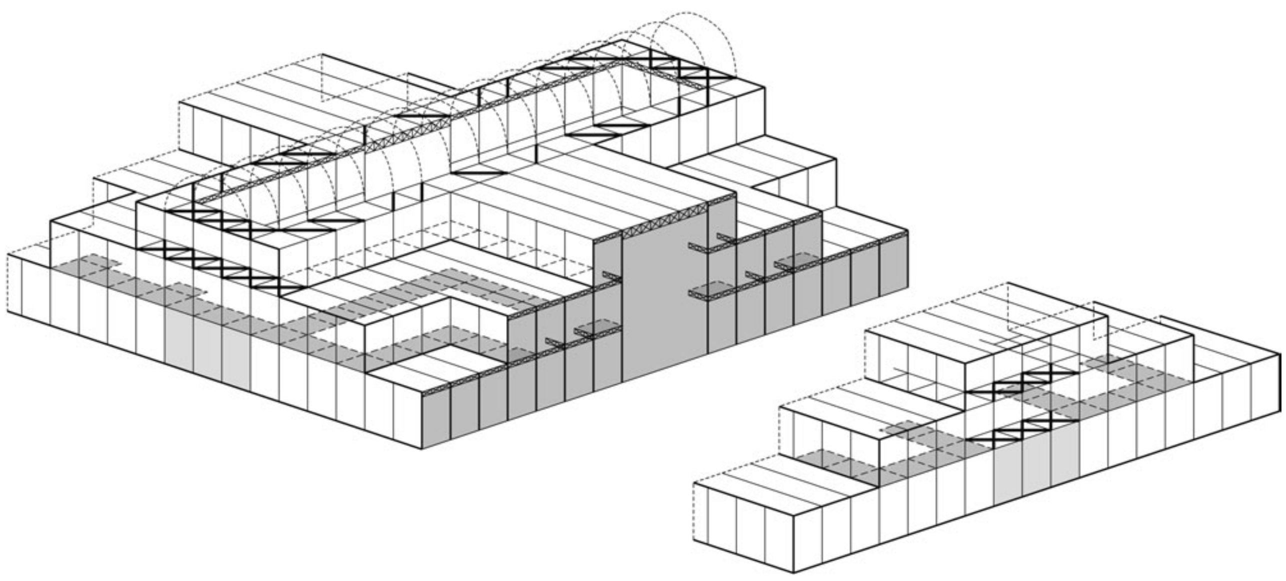
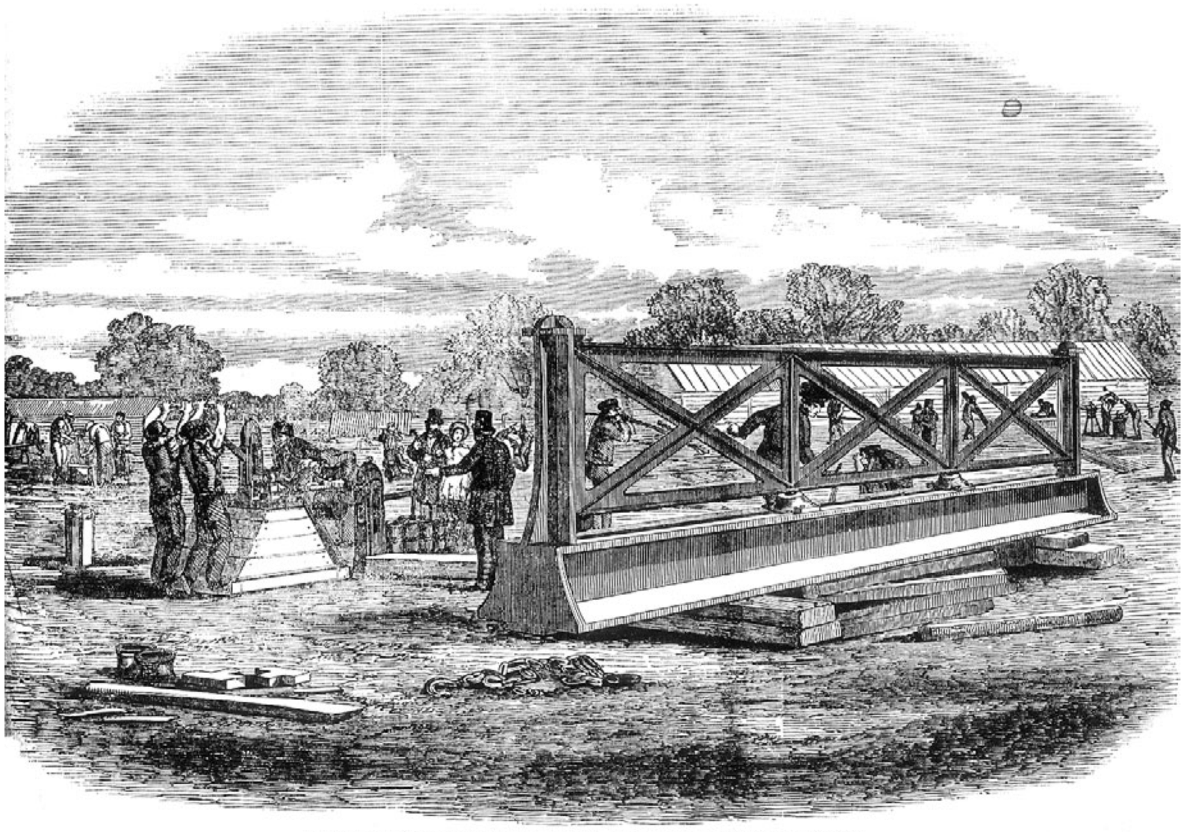
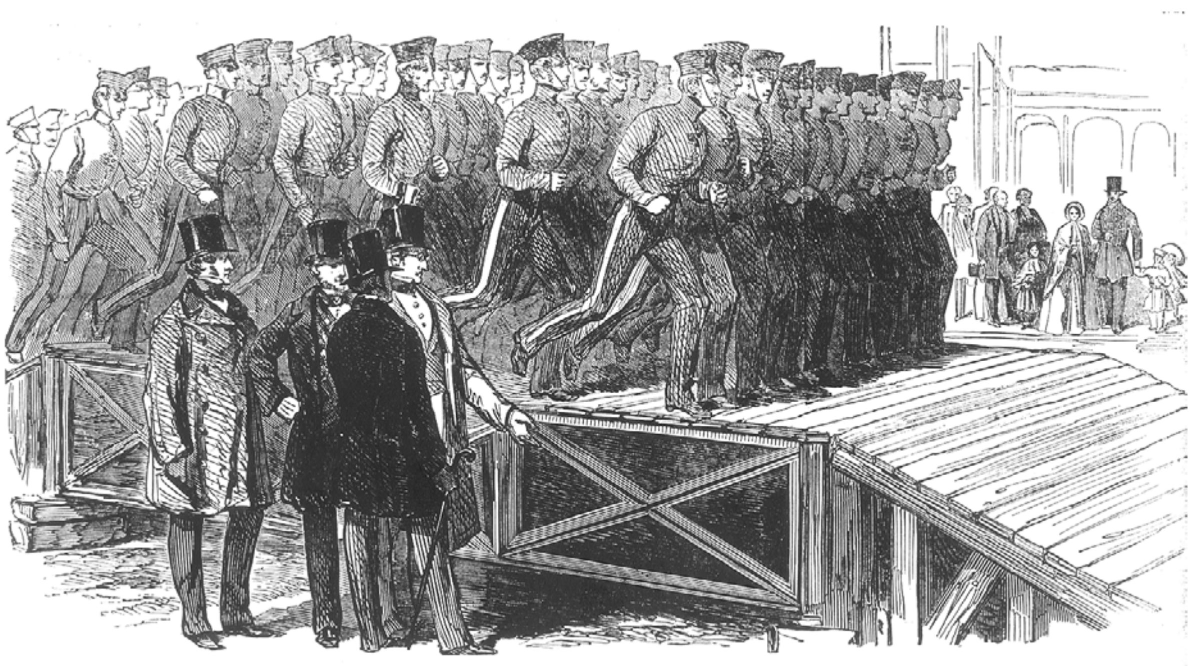


Figure 10. Drawing showing
– location of twenty-two sets of horizontal wind-bracing to the facades at the ends of the nave and transept
– horizontal truss under the lead flats to carry the vault thrust and wind loads to the main structure and down to ground
– the horizontal bracing to the façade provided by the gallery floors
(Bill Addis).



THE GREAT EXHIBITION BUILDING IN HYDE-PARK.—TESTING THE GIRDERS.—(SEE NEXT PAGE.)

Figure 11. Bramah hydraulic test rig for the 24-foot cast iron girders (ILN).



TESTING THE GALLERIES OF THE GREAT EXHIBITION BUILDING.—(SEE NEXT PAGE.)

Figure 12. Sappers enlisted to test the strength of the gallery floor structure (ILN).

the perfect regularity of their step, in marking time sharply, appeared a remarkably severe test, no damage resulted from their evolutions.'

Still the sceptics were not satisfied for, it was argued (rightly), testing one bay on the ground gave little confidence about the safety of the 400 or so bays in the gallery of the building itself. So Mr Field, a former President of the Institution of Civil Engineers, devised a mobile loading rig to test every bay *in situ*. It consisted of eight square frames, each housing 36 cannon balls weighing 68 pounds. These frames with their 288 cannon balls, weighing a total of eight and three-quarter tons, equivalent to 100 pounds a square foot, were trundled to and fro over about half the area of galleries with no resulting damage until, finally, "the experiment was considered decisive and a persistence in it was deemed unnecessary".

4. CONSTRUCTION

4.1 Detailed design

When the Paxton / Barlow / Fox Henderson team was awarded the contract, the design was still only a scheme and a great many details still had to be worked out. This work was undertaken by Charles Fox and John Henderson. Full design calculations were undertaken to establish the loads in all the columns and girders, for which purpose the team enlisted the help of Charles Wild, and they were sized accordingly. To calculate the sizes of the horizontal bracing to the arches of the transept, their lateral thrust was estimated. Given the careful attention given to wind-bracing, it is also likely that wind loads were calculated, but there is no record of the values of wind pressure assumed.

The effect of solar heating of the structure was much discussed as the design for the building developed. One concern was that the cast iron columns would be forced to bend, a structural action and loading that had not been considered in their design. The oak wedges had been introduced in the longitudinal connections between columns and girders to minimise this tendency, but sceptics argued that this would not be sufficient. Since there was no evidence of any problems after completion, we can only assume that the rigid connections and wedges were indeed adequate for their purpose. Despite the lack of problems, it would be interesting to know how often, if ever, the 20,000 or so wedges were checked for tightness.

4.2 Erection of the building

The columns and girders were easy to lift into place and the rigid connection allowed the frame to be constructed with a minimum of temporary support – here we see the portal action of the frame working before the cross-bracing had been fitted. [Fig.13] At first, placing the glazing proved a slow process until

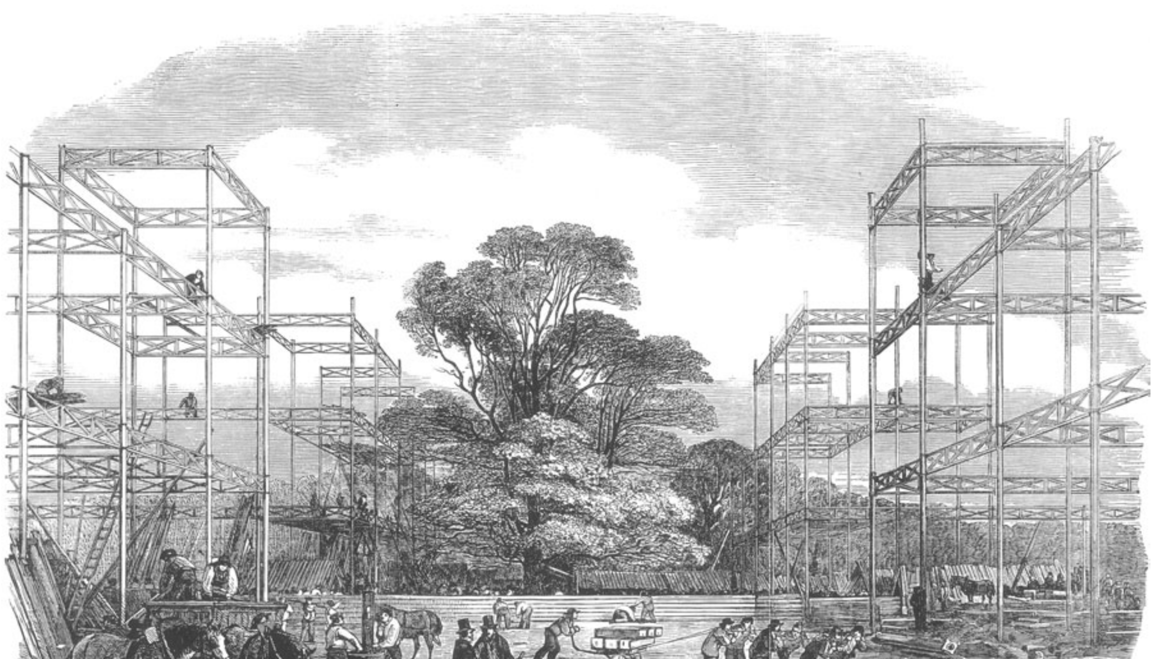


Figure 13. Structural frame under construction; note lack of cross-bracing and temporary works (ILN).

Charles Fox devised a trolley running in the Paxton gutters to speed thing up. [Fig.14]

The most spectacular stage of the construction was raising the arches to cover the transept. [Fig.15] The individual timber ribs were too slender to lift into position without twisting and breaking. Even if they had been raised singly, they would then have required temporary support while the entire roof was assembled. So pairs of ribs were pre-assembled at ground level to form eight bays of the vault, including all the timber purlins and wrought-iron diagonal bracing. Additional temporary iron bracing was fitted and each of the eight vault bays was lifted at the crossing of the main aisles in the very centre of the building. The lift took one hour and, once aloft, each assembly was placed on a tramway and rolled along the length of the transept and lowered the final four feet to its final location. This left a one-bay gap between each assembly which was later bridged by the purlins and diagonal bracing. [Fig.16] All eight sections of the vault were raised in just eight

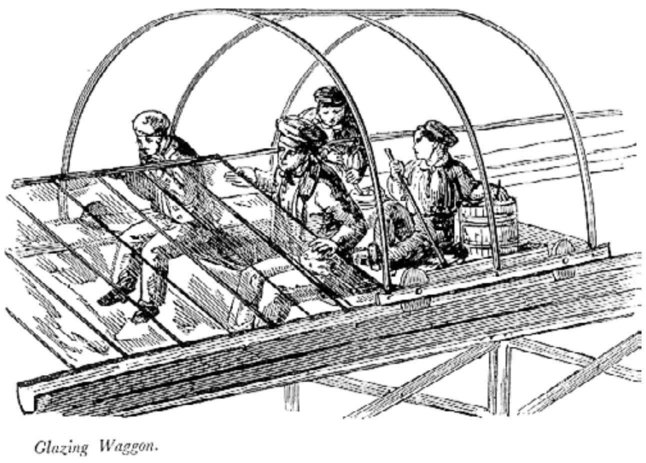


Figure 14. Glazing wagon devised by Charles Fox (ILN).

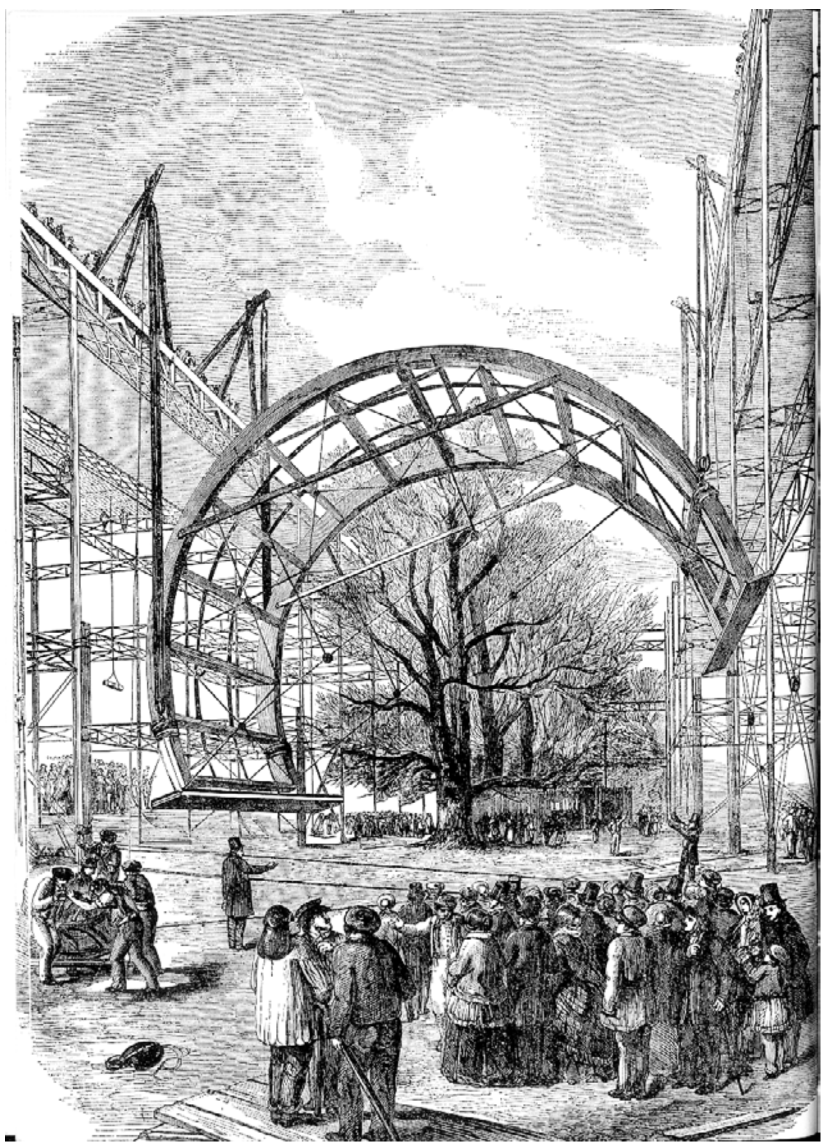


Figure 15. Raising the first prefabricated bay of the transept vault (ILN).

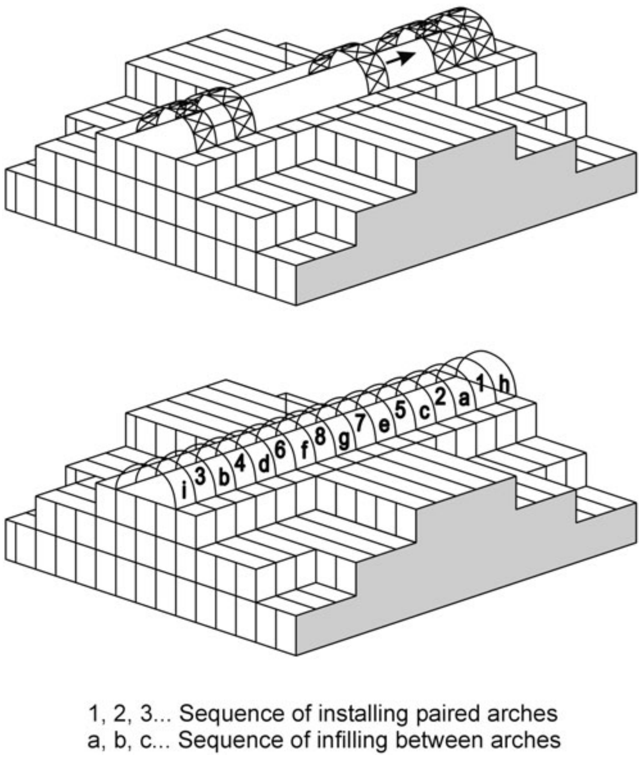


Figure 16. Probable sequence of raising and installing the prefabricated bays (Bill Addis).

days. The final bay at each end was fitted when the end façade of the transept had been erected to full height. [Fig.17]

4.3 The construction programme

The speed with which the structure was erected was almost incredible – 7 hectares of building were made watertight in just 27 weeks and the building was handed over to the decorators and exhibition planners on 31st January (a 4-week extension had been granted to incorporate a number of design changes made by the Royal Commission). The beam and column system devised to achieve rapid construction was a complete success. The quantities of goods to be delivered to site were enormous and the traffic jams in respectable west London were horrendous.

At the time the feature of the construction that attracted the greatest public attention was the large amount of manufacturing that was carried out on site. As soon as a portion of the single storey aisles of the Palace had been completed, it became a covered workshop with a six horse-power steam engine providing rotary power to drive the machinery for sawing, shaping, routing, planing, and drilling the remaining timber components.

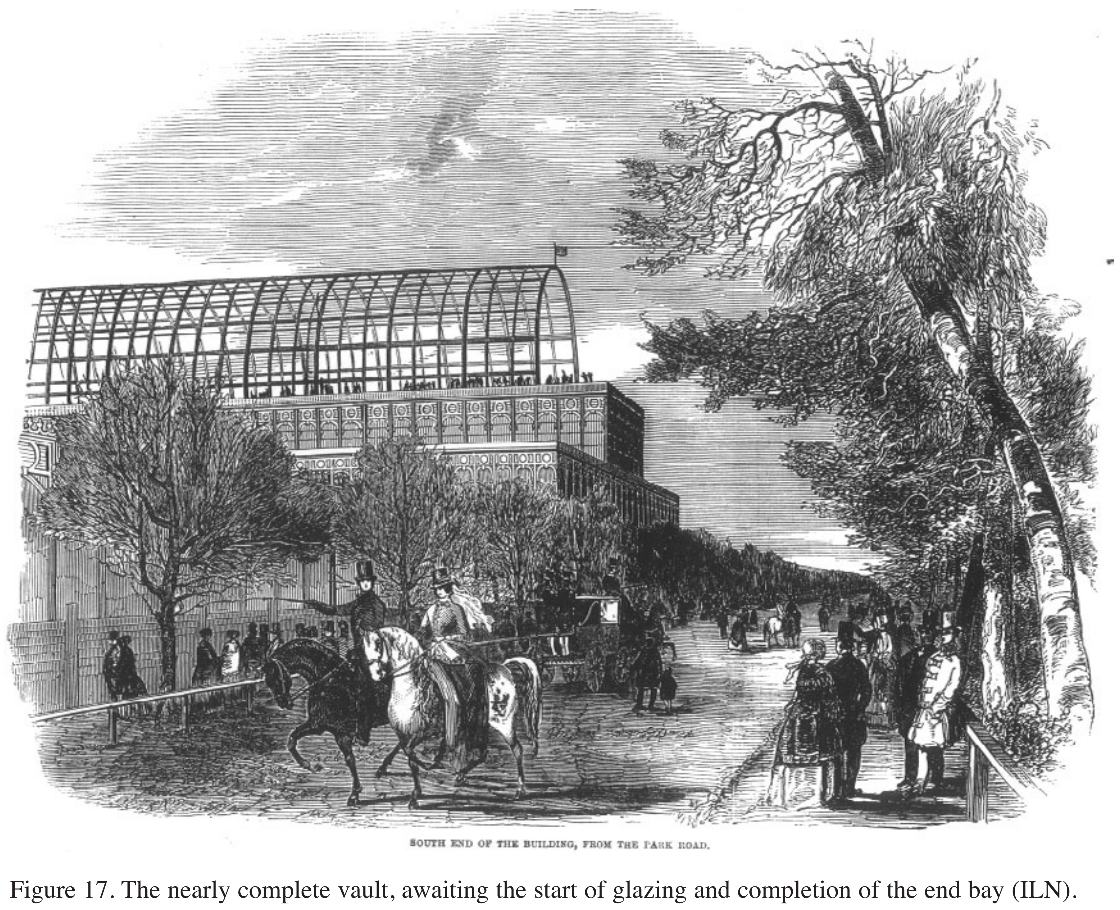


Figure 17. The nearly complete vault, awaiting the start of glazing and completion of the end bay (ILN).

Deliveries to site	
1107	Cast-iron column bases
2494	Cast-iron column shafts
2500	Cast-iron connections
2357	24 ft cast-iron girders
128,207	other cast-iron items
400,417	wrought iron pieces
293,655	panes of glass, 4ft × 2ft
264,972	pieces of machined timber
412,634	cubic feet of rough timber for machining on site
Maximum production rates achieved	
200	number of columns / week erected in October
310	maximum number of columns erected in 1 week
50	cast-iron girders delivered from Euston Station in 1 day
316	24 ft girders delivered in 1 week
16	wrought-iron girders fabricated in a day
7	48 ft trusses erected in 1 day
16	number of minutes taken to erect 3 columns and 2 24ft girders

[Fig.18] Also on site in Hyde Park were machines for cropping, sawing, punching and drilling the wrought iron strip used to fabricate the great 48 ft and 72 ft wrought- and cast-iron girders.

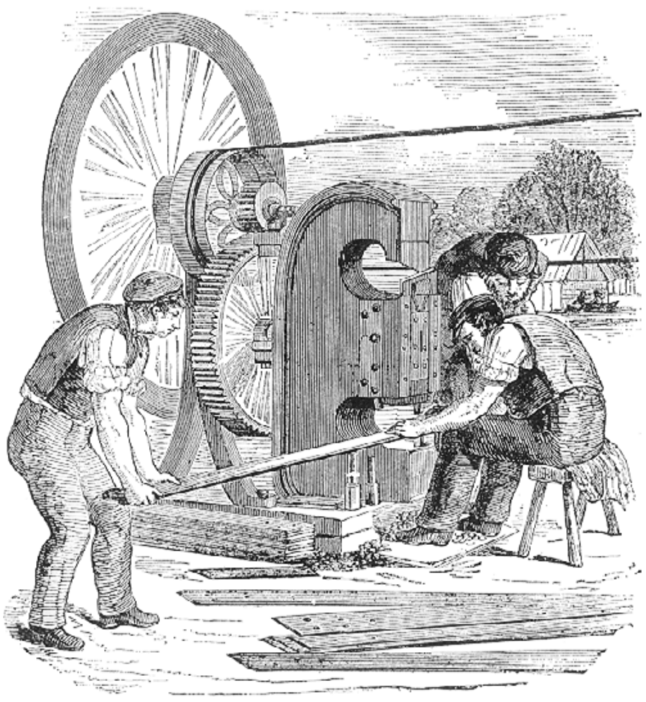


Figure18. Punching / cropping machine for on-site manufacture of wrought-iron components of 48 and 72 foot trusses (ILN).

4.4 After the opening of the exhibition

The building performed without problem during the summer of 1851 and the exhibition closed on 11th October after six million visitors had been through its doors. Although originally intended to be dismantled immediately, the building was granted a stay of execution while plans to convert it into a permanent 'Winter Palace' were discussed in the press and debated in Parliament. This plan was finally denied in April 1852 and an alternative led by Paxton was begun. The Hyde Park building was purchased from Fox Henderson who had retained ownership, and designs were made for a new and much larger Crystal Palace to be built in Sydenham in South London using the original components and many more. This building was opened by Queen Victoria on 10th June 1854 and enjoyed a long and successful life hosting a wide variety of public events until it was destroyed by a terrible fire on the night of 26th November 1936 that lit up the whole of south London.

5. THE ENGINEERING CONTEXT OF THE CRYSTAL PALACE

Despite its unprecedented appearance, nearly every aspect of the Crystal Palace design had been used before, in buildings or in other manufacturing industries. The key people involved in the project were able to bring a knowledge of materials technologies, design practice, construction experience and building precedent. It should also be remembered that the engineering and building community was quite small in 1850 and they nearly all knew each other. Meetings at both the Institution of Civil Engineers and the Royal Institute of British Architects were regularly attended by the famous names we still know today. In the days before a technical and professional journalism, meeting together, either at formal events or socially, was the principal way in which experience was shared.

5.1 Materials and structures

Cast iron

By 1850, cast iron had been used in buildings for over fifty years and every large iron foundry in the country would have been familiar with such construction [14]. Both Paxton and Barlow knew some of the very earliest buildings that used cast iron columns and beams – the many multi-storey mills in the Derwent valley between Matlock and Derby, just a few miles from the Chatsworth estate. The structure of such mills was a masterpiece of economy and sophisticated production engineering [15, 16]. By the 1840s they incorporated beams whose elevation reflected the bending moment they had to carry, and whose I-section was the most efficient way of using the expensive cast iron. The iron armature of the buildings could be assembled incredibly quickly, with no need for riveting or bolting. Then as now, the speed of construction was limited by the wet trades – the mortar in the masonry walls and the brick jack-arch floors. These were eliminated in the Crystal Palace.

Wrought iron

Wrought iron was a familiar construction material, not only as the fire-resistant material for making the roofs of theatres and mills, but also for hundreds of bridges and a growing number of station roofs throughout the railway network [17]. Richard Turner, for example, had completed the 50-metre span of iron and glass roof over Lime Street Station in Liverpool in 1847. Finally, the 1840s saw the construction of a number of iron frame structures at various naval dockyards in Britain to cover the slips where ships were built or repaired [18]. Such buildings at Pembroke (Fox Henderson, 1845), Portsmouth (Baker, 1846), Woolwich (Fox Henderson, 1847) presented unique challenges that stimulated their designers to produce imaginative and economical solutions.

Glass

The glass industry had enjoyed a period of growing prosperity in the early nineteenth century despite the tax on windows in Britain that was only lifted in 1852. This led directly to the production of larger panes of glass for horticultural glass houses for which maximum solar gain was an important requirement. Glass houses had been fashionable additions to most large estates since the 1820s [19]. The palm house at Bicton Gardens, near Exeter was completed in 1820. In 1827 Charles Fowler had built the iron and glass dome at Syon House which also had a sophisticated heating system designed by Thomas Tredgold. Glass houses soon featured in public gardens – Loudon constructed one at the Botanical Gardens in Edgebaston in 1831; the Jardin des plantes in Paris dates from 1833; Richard Turner built his glasshouse in Dublin in 1839 and worked with the architect Decimus Burton on the palm house at Kew which was completed in 1847.

Laminated timber

The timber arches over the transept, comprising three vertical planks bolted together was similar to the system developed by Philibert de l'Orme in the 1550s which was well-known to nineteenth century architects. Sidney Smirke had used the idea for the Pantheon Bazaar on London's Oxford Street (1833–4) and Paxton had used it for his glass house at Chatsworth in the late 1830s.

5.2 Production engineering

The 1830s and 1840s saw a rapid expansion of iron foundries able to produce large iron castings and rolling mills able to produce rolled, wrought-iron sections (flat bar and L-sections at that time). Ever larger machines were being built for using in factories making components for steam engines, spinning, weaving and printing machinery, locomotives and ships. These machines were able to shape, drill, cut and rivet iron with great ease. There were also great improvements in mass production and the production of identical, interchangeable components, any one set of which could be assembled to produce a whole artefact. The idea of making interchangeable parts (as opposed to hand-crafted bespoke and unique components) dates back at least to the 15th century in the spinning and weaving workshops of Medici Italy where the wearing parts of machines were mass-produced in cottage workshops, to be used in any machine. The idea was brought into the silk mills of Nottingham and Derby in England in mid-18th century. In around 1810 Marc Brunel had developed his machinery for mass-producing the components to make pulley blocks for the navy, and by the 1840s this rational attitude to making things, especially from cast and wrought iron was commonplace – iron castings, by their very nature, are identical, and rolled iron sections were also of standard, interchangeable sizes.

6. THE STRUCTURAL ENGINEERING LEGACY OF THE CRYSTAL PALACE

The fame of the Crystal Palace around the world ensured that all the engineering ideas used in its design and manufacture became known to nearly every builder in the industrialised world, and it was widely copied.

Regarding the development of structural engineering, and especially the widespread adoption of the iron and steel frame, a number of buildings that followed the Crystal Palace are of note.

- The Oxford Midland Railway Station (1852) used virtually the same cast and wrought-iron girders used at the Crystal Palace [20].
- James Bogardus used an open frame of cast-iron columns and beams for a 100-foot tower to carry a fire alarm bell in New York in August 1851 [17]. These had bolted rigid connections and he used the same idea again in 1855 for a shot tower, in which the voids of the iron frame were filled with brick panels.
- When the Crystal Palace was re-erected at Sydenham in South London in 1852–53, Isambard Brunel used cast-iron columns and beams, bolted together, for the structure of the two water towers at the site.
- In 1853 Godfrey Greene designed an iron roof at Chatham docks in which the stability is provided by frame action (with no masonry walls) [19].
- In 1858–60 Greene built the boat store at Sheerness which was the first multi-storey iron-frame building using rigid connections to provide stability and carry wind loads [21]. [Fig.19]
- In 1865 a warehouse was constructed at St Ouen docks in Paris in which the iron floors beams were carried by iron columns, and the masonry walls were non-load-bearing.
- In 1872 the Chocolate Factory, with a frame made entirely of wrought iron, was completed near Paris, by architect Jules Saulnier and engineer Armand Moisant.
- In 1878–79 William le Baron Jenney first used wrought-iron columns and beams in the Leiter Building in Chicago.

7. CONCLUSIONS – THE PLACE OF THE CRYSTAL PALACE IN STRUCTURAL ENGINEERING HISTORY

As with most developments in the structural engineering of buildings, virtually nothing in the Crystal Palace was entirely new and without precedent. Nevertheless, it deserves its place as one of the most innovative buildings of all time because of the large number of ideas that were brought together to achieve an outcome that would surely have been impossible using any other form of structure.

Figure 19. The Boat Store, Sheerness (1858–60), in which stability of the frame is achieved with rigid-jointed cast iron columns and cast and wrought iron beams. (Bill Addis)

As Henry Cole, the overall coordinator of the exhibition, said in his memoirs:

> *"the one object with which the world first became acquainted for the first time . . . was the building itself which Paxton suggested. The Exhibition has taught the world how to roof in great spaces; how to build with iron and glass in a way never done before . . . Nothing very novel in iron columns resting on concrete foundations; nothing novel in Paxton gutters, which half a dozen persons claim to have invented, but something very novel in covering twenty acres with glass as an exhibiting room."*

The engineering design of the building is pervaded by ingenious devices that enabled it to be constructed so economically and rapidly. The main ones were these:

- the use of cast iron to provide identical batches of components quickly and cheaply
- the rigorous use of a modular approach (based on 8 feet) to developing both plan and elevation
- the use of rigid frame action to provide (at least some) stability
- the use of a frame system that could be extended in two directions (previous use of structural iron could generally be extended in one direction only)
- the use of wedges to fit girders and columns, rather than bolts or rivets
- the inherent stability of the frame during construction which enabled scaffolding to be avoided

- the two-way spanning sub-structure of the gallery floor to distribute loads equally
- the use of post-tensioning to introduce pre-camber into the Paxton gutters
- the use of the transept as a means of providing more lateral stability to the "nave"
- the overt use of diagonal bracing (now called cross-bracing) to provide additional stability and clear load paths carrying wind loads (maybe the first overt use of cross-bracing?)
- the use of horizontal cross-bracing in the "lead flat" portion of the roof to carry the thrust of the transept vault and wind loading on the transept to the main frame, and thence down to the ground via the vertical cross-bracing
- the widespread use of mass (or at least batch) production which, among other benefits, meant the workforce did not have to keep learning new construction details and methods
- the widespread use of small (lightweight – 1 ton max.) components that could be easily manoeuvred
- the use of a slatted floor at ground level to facilitate cleaning (although sweeping machines were available, it was found that "the dresses of the female portion of the visitors performed this office in a very satisfactory manner").

The Crystal Palace opened the world's eyes to the possibilities of applying the techniques of manufacturing engineering to building construction and how the skills of the structural engineer could be used to achieve this goal.

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APPENDIX
The people behind the Crystal Palace

Joseph Paxton (1803–1865)

Paxton was clearly the inspiration behind the scheme for the Crystal Palace. He had trained as a gardener in the early 1820s, including a spell at Kew Gardens, before obtaining the post of head gardener at Chatsworth in 1824. He gradually took on more and more responsibility at Chatsworth and was soon the manager of one of the largest and wealthiest estates in the country. Of particular significance is the experience he had gained in constructing the enormous conservatory at Chatsworth in 1836–40 and he used all the ideas he developed at Chatsworth in his proposals for the Crystal Palace.

Paxton was also familiar with many of the greenhouses that were being constructed in gardens in Britain and knew Charles Loudon's book which illustrated ridge and furrow roofing in 1822. At Chatsworth he had the opportunity to experiment with many ideas and to resolve the many teething problems that new ideas always throw up. His experimentation with the ridge and furrow system on a number of buildings led to his preference for combining glass with timber rather than with iron, as was the usual practice with glass houses. This experience was all vital for Paxton's greatest achievement, the Great Conservatory at Chatsworth in which he used the ridge-and-furrow system on a curved roof made of laminated timber arch ribs, spanning about 72 feet, the same size he would use for the arch at the Crystal Palace. This arch was supported on cast-iron columns which were stabilised in the longitudinal direction by cast-iron girders, each carrying two bays of the ridge-and-furrow roofing (about 15 feet). The cast-iron columns were hollow to carry rainwater to an underground drainage system. The glass used for the roof at Chatsworth was supplied by Chance Brothers, made using the cylinder glass process, they had imported from France in 1832, and supplied in 48 inch lengths, just as he would use at Hyde Park. For the Great Conservatory at Chatsworth, Paxton also arranged for a bespoke routing machine to produce the 40 miles of sash bar the conservatory needed.

William Barlow (1812–1902)

Barlow was the son of the eminent engineering scientist Peter Barlow whose book on timber engineering, published first in 1817 and in many later editions, was widely used. Peter lectured at the Woolwich military engineering academy for forty years and it was at the Woolwich Dockyard that William served his engineering apprenticeship. He later worked on the construction of London Docks and worked for six years in Turkey constructing various industrial buildings. On his return to England in 1838 he worked as an assistant engineer to the Manchester and Birmingham Railway, and in 1842 he joined the Midland Railway, of which Paxton was one of the Directors. William's excellent understanding of structural engineering and experience with both cast and wrought iron augmented Paxton's own experience. It was Barlow who developed the overall structural engineering concept for the Palace that was developed in detail by Charles Fox and John Henderson.

Charles Fox (1810–1874)

Fox was the principal structural engineer for the Crystal Palace, and founding partner of the firm Fox Henderson that built it. He began working on the scheme within a week or two of Paxton and Barlow having developed their original scheme. During the autumn of 1850 Fox was responsible for producing the tender drawings for every last component of the building, working up to 18 hours a day. He was rewarded with a knighthood for his contribution to the project [22]. Fox was born in Derby and had trained with Captain Ericsson in Liverpool. At the age of just 22 he patented the switch point for railways which was soon universally accepted as an improvement on the old sliding rail technique. He worked for Robert Stephenson on the London and Birmingham railway, and was entrusted with designing the tunnel at Watford. In 1837 Fox set up in practice by himself as a consulting engineer and was soon joined by the young Herbert Spencer who worked as his assistant on the design of the all-wrought-iron roof of Euston Station in 1837. In 1841 the Scotsman John Henderson joined the firm and in 1845 Fox re-formed the business in partnership with John Henderson, under the name of *Fox, Henderson and Co.* of London, Smethwick, and Renfrew.

This firm was one of the first to manufacture the full range of iron goods for the railway industry, including roofs, bridges, cranes, tanks, and railway wheels. Fox, Henderson executed considerable work on railway structures and iron bridges in England and Ireland and on the Continent, in France, Switzerland, Germany and Denmark. Of particular significance to the firm's structural work at Crystal Palace are the long-span iron roofs the firm constructed over slips at the Royal Dockyards at Pembroke and Woolwich in 1844–47 [18]. While working on the Crystal Palace, the firm was also involved in the construction of the Oxford Midland railway station which opened on 20 May, 1851 [20]. Immediately after Crystal Palace the firm won the contract to build the roof over Paddington Station in 1851–53. The firm later constructed the new Birmingham New Street station with its enormous roof in 1854 which, spanning up to 65 metres, was then the world's largest railway roof. This was designed by Fox and E. A. Cowper, with additional help from Robert Bow using his new graphical method of structural analysis to calculate the forces that each structural member would need to carry.

John Henderson (1811–1858)

Henderson was a Scottish engineer who joined Fox's firm in Birmingham in 1841 and became a senior partner of the firm *Fox Henderson & Co.* in 1845. He had worked on several of the large roofs the firm built over ship docks and for railway stations, as well as countless smaller iron structures for the railways. He brought to the Crystal Palace a wealth of practical experience in production engineering, project and site management and was the man who ensured that things got done, both by the various sub-contractors supplying goods and on the construction site itself. His (metaphorical) descendants are still to be found on every major construction site today. They have to combine a profound understanding of construction techniques with the ability to remember to chase a thousand and one outstanding actions that need to be done, and to get dozens of men "on your side" who will move heaven and earth to get something done for you when it really matters. While we know little of Henderson's character, he must have had all these talents, and probably many more.

Charles Heard Wild (c.1819–1857)
Wild had worked in Fox, Henderson's Birmingham office in the mid-1840s before working with Robert Stephenson on the design of the tubular bridges at Conwy and Menai – all this before he was 30 years old.

Robert Stephenson (1803–1859)
Robert was the son of George Stephenson who was one of the founding fathers of the railway system in Britain in the 1820s and 1830s. He was a member of the Building Committee for the Crystal Palace. Robert worked mainly as a civil engineer on the construction of many hundreds of miles of the rail network, including some of the most spectacular iron bridges of the age, notably the Britannia Tubular Bridge. By 1850 he was already one of the most eminent engineers of the day; in 1849 he had been elected the first and in 1855 became the President of the Institution of Civil Engineers.

William Cubitt (1785–1861)
Sir William Cubitt played a key role in the whole Crystal Palace project. He was the chairman of the Building Committee and became the overall project manager overseeing detail design and construction. He had to be consulted about all the key decisions and all drawings required his signature before they went off to the manufacturers and fabricators. Behind him he had a lifetime's work in engineering and managing large railway and canal construction projects and presided over the project with the voice of experience. He was the current President of the Institution of the Civil Engineers and was awarded a knighthood for his contribution to the building of the Crystal Palace.

Isambard Brunel (1806–1859)
Brunel was a member of the Building Committee for the Crystal Palace. He was, and is, arguably the most famous engineer of the 19th century and author of a host of enormous achievements ranging from the Great Western Railway, Paddington Station in London, countless railway locomotives, the iron ships Great Britain and Great Eastern, several tunnels, the Royal Albert Bridge, Saltash, and the Clifton suspension bridge in Bristol.