# Decorative Use of Iron in the Structures of Buildings – Overview

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## 1. History of Iron in Buildings (up to 1800)

The earliest trace of iron's structural use in buildings comes from the Pagodas (tiered towers) built with cast iron and bronze in 9th Century China (and onwards).

In Europe, tension chains made of iron were used to restrain the masonry domes of St. Paul's Cathedral (built late 1600s) and St. Peter's Basilica (chains installed in repairs mid 1700s). These could be regarded as the first 'structural' use of iron in Europe (Chang & Swenson, 2020).

Use of iron in actual structural elements (in Europe) began in the late 1700s, as technical developments in blast furnace technology drove the price and complexity of cast iron manufacture down, namely:

- Use of coke instead of charcoal as combustible material, which was cheaper and more available.
- Use of steam engines to blast air into the furnace, increasing efficiency and mobilising the use of waterpower.
- Replacement of leather bellows with cast iron blowing cylinder, which was much more durable.

The production of wrought iron also benefitted from the industrial revolution through the invention of the 'puddling' process in 1784 by Henry Cort. Whilst superior to cast iron in its tensile strength and ductility, wrought iron was still notably more expensive to produce (Chang & Swenson, 2020).

The structural use of iron in buildings was not considered aesthetically pleasing at first, however it presented some significant practical benefits which brought about its initial use in industrial buildings. Iron columns could carry floor loads using smaller sectional areas than masonry columns, increasing usable workspace. Cast iron was also much more resistant to fire and corrosion than wood. Fire in particular was a serious consideration, as catastrophic fires were commonplace in the industrial sector at the time (Van Dyke, 2004).

The benefit of iron structural members was first realised in the construction of St. Ann's Church, Liverpool, in 1773. The church used solid columns made from cast iron. This is widely considered the first structural use of iron (in Europe). Another example of the primitive use of cast iron columns is a warehouse built in Milford, Derby, by William Strutt in 1793 (Chang & Swenson, 2020).

Ditherington Flax Mill, a textile mill built two years later in 1795, used cast iron for both the columns and beams. Cast iron T-beams were planted onto the load-bearing masonry walls and cast-iron columns were used as intermediate supports, spaced at around 3m. This building is regarded as the first 'real' cast-iron building. The blueprint for this building was used as a design basis for the many textile mills in Northern England that followed (Swailes & Marsh, 2005).

Due to higher production costs, wrought iron was not as popular as cast iron for structural use in early iron buildings. As iron building designs became more complex, requiring greater spans, wrought iron was used increasingly for elements in tension or bending. The first structural use of wrought iron is in the roof truss of the Theatre-Francais in Paris, built in 1786. The roof, spanning 28m, was made of flat wrought iron bars, connected with rivets (Chang & Swenson, 2020).

From an architectural decoration perspective, wrought iron was used extensively from the middle-ages onwards to create elaborate railings, doors, balconies and other external fittings. Cast iron was also used decoratively in buildings from the middle ages although to a lesser extent. An example use would be the depiction of scenes and figures in cast iron fire backs.

Wrought iron, formed through working iron ore with a hammer, could form decorative elements comprising more slender, elegant members than cast iron. Following the aforementioned reduction in cast iron production costs, decorative railings and fences began to appear in many more 'lower-status' properties, all made from cast iron, with a lacey aesthetic to mimic a wrought iron construction.

Particularly in use in verandas, such as those in New Orleans, these railings could be built in conjunction with extremely slender 'columns' of the same lacey aesthetic. These columns often bear small loads. An example is seen in Figure 1 below.

Figure 1. Decorative cast-iron veranda in French Quarters of New Orleans

## 2. Building Regulations (up to 1900s)

The turn of the 20th Century marked several milestone moments for the regulation of buildings.

The General Powers Act of London County Council, created in 1909, popularly referred to as the 'steel act', first recognises and regulates metal construction. The act specified permissible loads on floors, limiting stresses on structural members, and required design details including calculations to be deposited to the District Surveyor. It generalises permissible metal framed structures as *'buildings wherein the loads and stresses are transmitted through each storey to the foundations by a skeleton framework of metal or partly by a skeleton framework of metal and partly by a party wall or party walls.'* (Bates, 1991).

Prior to these Acts and Standards, no real nationwide regulation for iron buildings was in place. Generally speaking, the responsibility for a safe structure was heavily placed at the feet of the designing engineers. There were however several different ways in which the stability of iron buildings could be regulated locally, and safe design practices normalised (De Bouw & Wouters, 2015).

The London Building Act of 1774 first introduced the appointment of surveyors to 'double-check' building designs and oversee building construction. The District Surveyors Association was established in 1845.

Many public and private companies, for example railway companies, compiled and regulated their own set of design standards. Contractors and designers who did not adhere to these regulations would not be given business (J. Ley, n.d.).

In 1842, an Encyclopaedia of Architecture was first published. In an 1881 edition, advisable live loads were specified as 128 lbs/sq.ft (6.13 kN/m2) for light workshops, public halls and churches; and 100 lbs/sq.ft (4.8 kN/m2) for private dwellings (Bates, 1991).

A handbook published by Dorman Long and Company in 1887 gives the safe distributed loads on beams at 3rd, 4th and 5th of their 'breaking strain'. This demonstrates the concept of limiting safety factors was operational from at least the late 1800s, likely some time before (Bates, 1991).

The Smeaton's Formula, published in 1759, demonstrates that wind loading has long been considered in building / structure design. The original formula states $P = 0.005V$, where P is wind pressure and V is wind velocity. Several years later the formula was amended to a less conservative $P = 0.003V$ following experiments undertaken at the National Physical Laboratory. Wind loading likely presents a real design rationale behind many of the 'openwork' style iron designs created at the time. (Bates, 1991) (Rodal, 2006).

## 3. Bibliotheque Sainte-Genevieve Reading Room

The Bibliotheque Sainte-Genevieve reading room was designed by architect Henri Labrouste and built between 1838 and 1851. The room uses a lot of decorative ironwork in its roof; however, it is the arched 'latticed' beams supporting the roof for which this building is most famous. These beams are regarded as one of the most famous examples of where cast iron structure and decoration are combined. The structure can be interpreted as lattice beams or shallow roof trusses.

The 'spikey, tight curled' details in the beams can be seen in some lamp-post designs undertaken by Labrouste and his brother in 1837 (Middleton, 1999).

The roof spans 19m, such a distance had been cleared in a single span many times before this building, however Labrouste used cast iron columns as an intermediate support. Works suggest this could have been a response to architectural critique at the time, or perhaps an ill-informed attempt to reduce material cost of the iron truss members (Middleton, 1999).

In terms of ensuring a safe design, the detail of the iron structure was developed with concurrent testing undertaken in the Louvre on prototypical models (Middleton, 1999).

As well as the roof, a great amount of decorative iron work is visible in the spandrels of the arches connecting the spine of intermediate columns (Clericuzio, 2013). Figure 2 show a view from within the room, Figure 3 shows a section detail of the roof and column spine drawn by Labrouste.

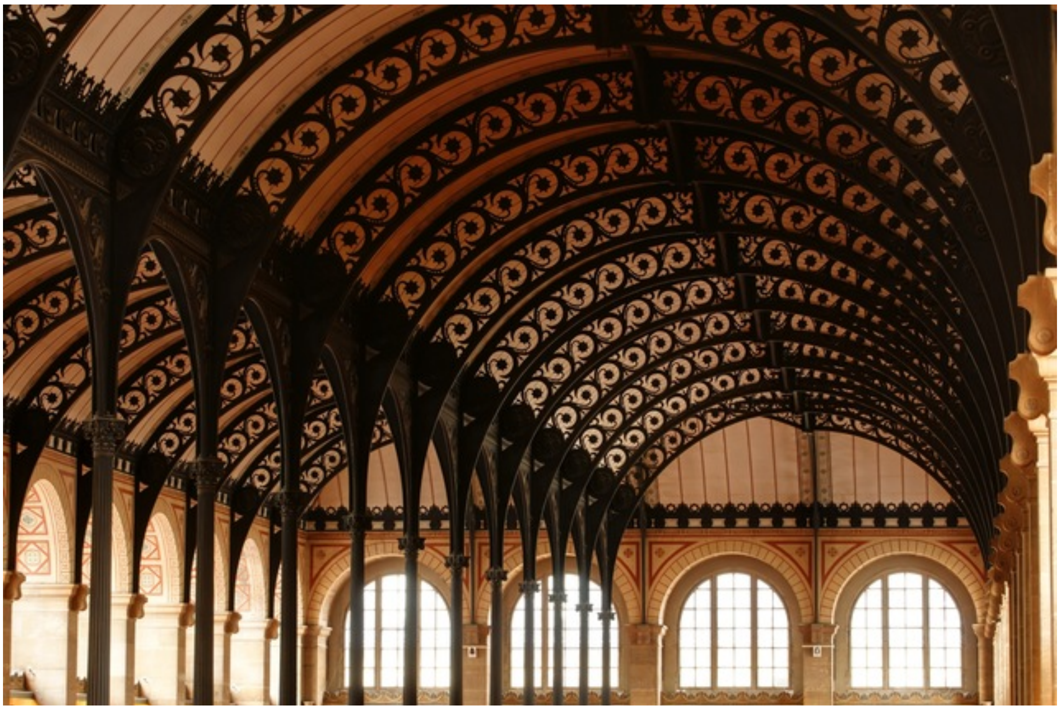


Figure 2. The iron roof and columns of the Bibliotheque Sainte Genevieve reading room

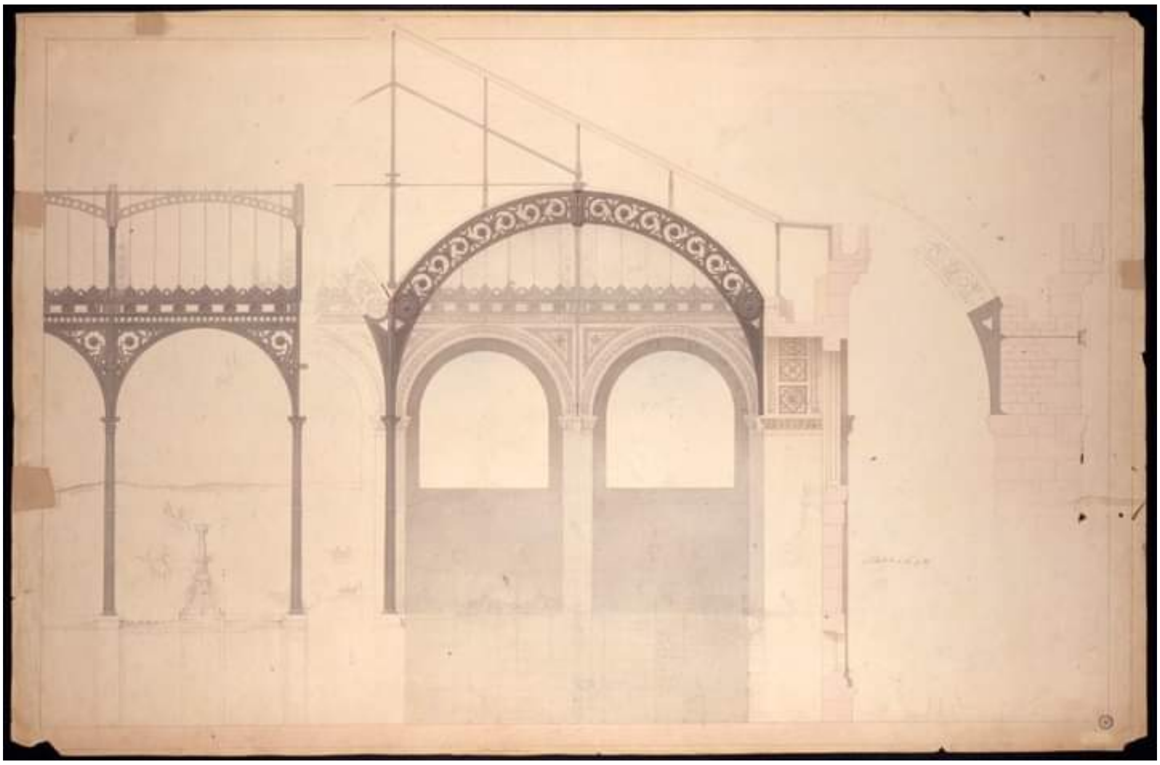


Figure 3. Section drawings by Labrouste of the BSG cast iron arch ribs and intermediate column spine (Clericuzio, 2013)

## 4. Bibliotheque Nationale Reading Room

Built in 1868, the reading room of the Bibliotheque Nationale is another of Labrouste's cast iron designs that has gained fame for its beauty.

In this structure, the roof is formed of a series of domes, each supported by cast iron arched beams. Unlike in the Bibliotheque Sainte-Genevieve, the web members of these arched beams comprise radial connections. Fixed between each radial element are diagonal cross plates. As well as providing some aesthetic beauty, these plates provide lateral restraint to the radial elements. This restraint would become increasingly crucial as the radial elements tend towards the arch springings, becoming increasingly orientated away from the vertical direction of loading.

Both of Labrouste's reading rooms are also well known for their exceptionally slender columns, contributing significantly to the elegance of the designs. Columns of this slenderness were only achievable due to the positioning of the arches in both buildings such that where each arch founds onto a column, there is an arch founding in the opposing direction. In doing this, the horizontal thrust exerted by each arch is largely cancelled out by its opposing neighbour. In spite of their beauty, columns of this slenderness would not pass modern Eurocode requirements, which have a limit on column slenderness to minimise the risk of buckling (Various, 2005) (Clericuzio, 2013).

Figure 4 shows a view from within the building, where the arched beams and slender columns can be seen. Figure 5 shows a more detailed view of the arched beams.

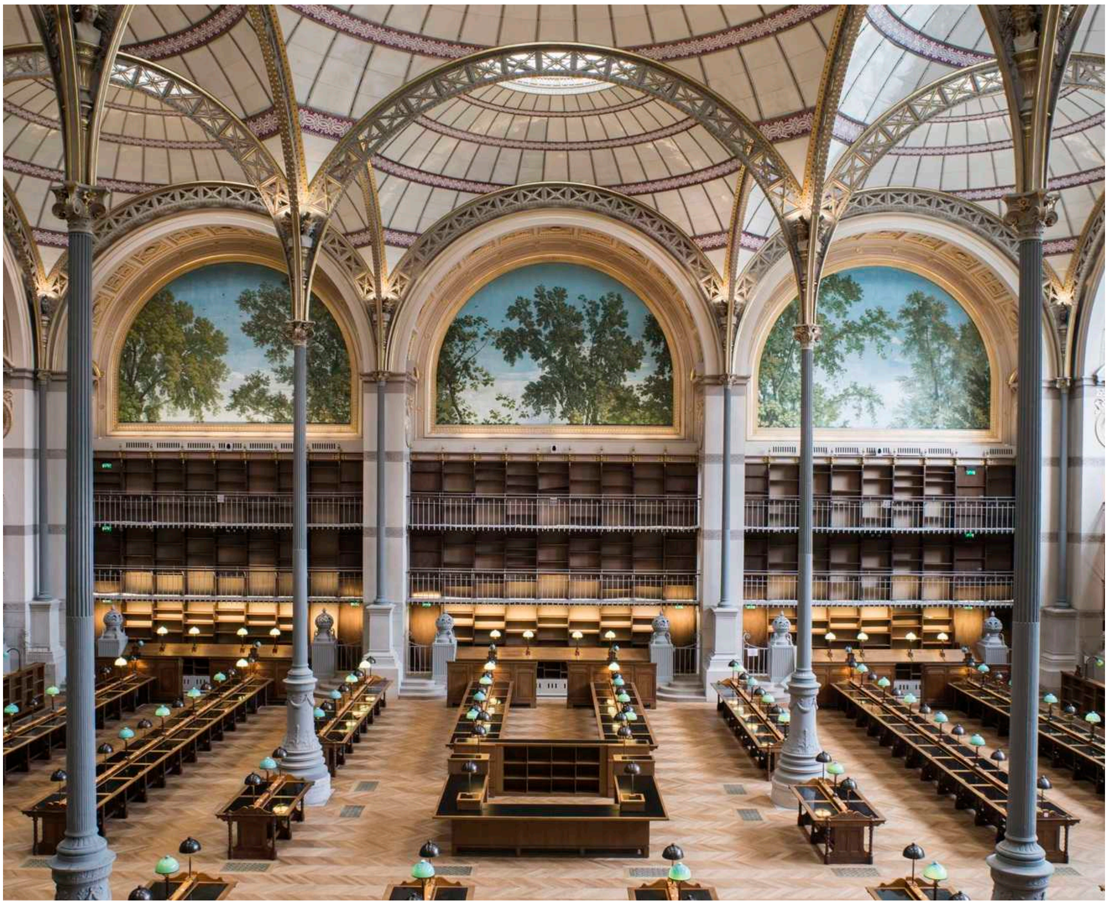


Figure 4. The iron roof beams and columns of the Bibliotheque Nationale reading room

Figure 5. Close up of the cast iron arch roof beams of the Bibliotheque Nationale reading room

## 5. The Eiffel Tower

The Eiffel Tower, completed in 1889, is a wrought iron monument standing 324m tall. It is named after Gustave Eiffel, a prominent French bridge engineer who headed its conception and delivery (Rodal, 2006).

As with the Bibliotheque Sainte-Genevieve, a key inspiration for the design of the Eiffel Tower is said to be 13th Century gothic architecture. The latticework with lacey aesthetic is a nod to the intricate detailings of stone elements used in gothic style (Barthes, 2012).

To achieve the towers height, it was necessary to design the four 'piers' of the tower (each comprising four columns) with a large breadth, particularly at the lower half of the structure. This presented a problem in terms of the lateral bracing proposed. As the breadth of each pier was so great, the length of the required bracing members was so great that bending caused by wind loading or column loading became excessive. To overcome this problem, bracing up to the second storey of the tower was formed by latticed beams, and included horizontal and vertical brace members as well as diagonal. This approach can be seen in the first two stories of the tower, before the four piers converge and reduce in breadth such that regular solid-section bracing is safe (Vogul, 1961).

Several works refer to the openwork style of the Eiffel Tower as a response to wind loading. As the tower was to be the tallest in the world at the time, it is reasonable to assume that a great amount of care was taken to reduce wind loading at these unexplored heights.

The arches of the tower that appear to support the first floor comprise two curved members connected with straight axial elements angled radially. Decorative iron detailing springs up and down from the beams between the connecting elements. The arches were in fact added for aesthetic purposes only, as an addition suggested to Eiffel by one of his architects. The rationale was to increase the impression of structural stability to the general public, and to present a grand gateway through which to enter the tower (TATA Steel, n.d.).

Flanking the arches in the spandrels either side are radially orientated elements. Whilst helping to emphasize the gateway effect, these elements would not be optimally orientated for transfer vertical loads. Vertical elements here would be more efficient from a structural perspective.

Figure 6. The arches and openwork cross-bracing of the Eiffel Tower

## 6. El Mercado Centrale, Santiago

Built in 1872, the Mercado Centrale provides a good example of how iron ornamentation was used to disguise structural design ideas as decorative contributions. The structure was designed by English architects / engineers, and manufactured in a Glaswegian foundry, before being shipped over to Chile. To accommodate the long transportation journey, the structure is designed to be assembled from many smaller elements as opposed to longer ones (Guedes, 2006) (The Engineer, 1870).

Due to its cheapness and decorative licence, the structure is made mostly of cast iron. Wrought iron was used only for the bolts and the tie-rods cross-bracing the roof frame, two small elements for which tensile strength was crucial (The Engineer, 1870).

Tie-rods are particularly necessary for lateral stability of buildings in earthquake prone regions. In the Mercado Centrale, the X-shaped form of the tie-rods is repeated in elements throughout the structure. In the middle of the structure is a raised roof, which allows light in through the additional wall space created. These light-emitting walls are formed of X-shaped trusses, which again provide lateral stability, decorated with lacey iron ornamentation.

The ceiling beams supporting the roofs are punctured with holes at regular intervals. As with the previously mentioned beam designs, the main structural benefit brought by these holes is a reduction in beam weight. The circular holes likely do not remove as much weight from the structure as the lattice beams designed by Labrouste. The holes could have been chosen due to the fact that the ceiling beams are in fact formed of many short beams bolted together. A latticed design would perhaps make this bolted configuration more obvious. As with the X-shaped trusses, the holes in the ceiling beams are decorated with iron ornamentation, such as the stars fixed central to each hole.

Figure 7 shows a photo from within the building, showing the X-shaped trusses and the perforated beams. Figure 8 shows a section detail of both the X-shaped trusses and the perforated beams.

Figure 7. The X shaped trusses and cellular ceiling beams in the Mercado Centrale

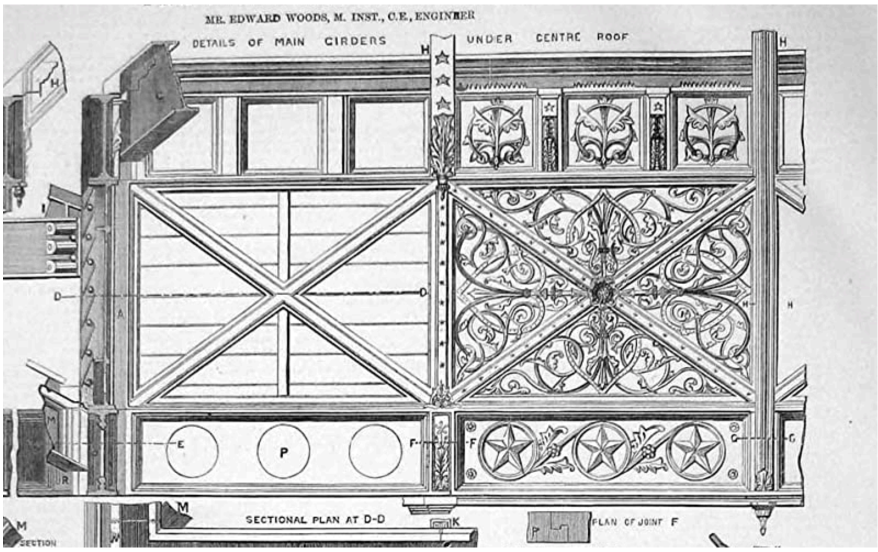


Figure 8. Section detail of the X shaped trusses and cellular ceiling beams in the Mercado Centrale (Woods, 1870)

## 7. St Pancras Station Train Shed

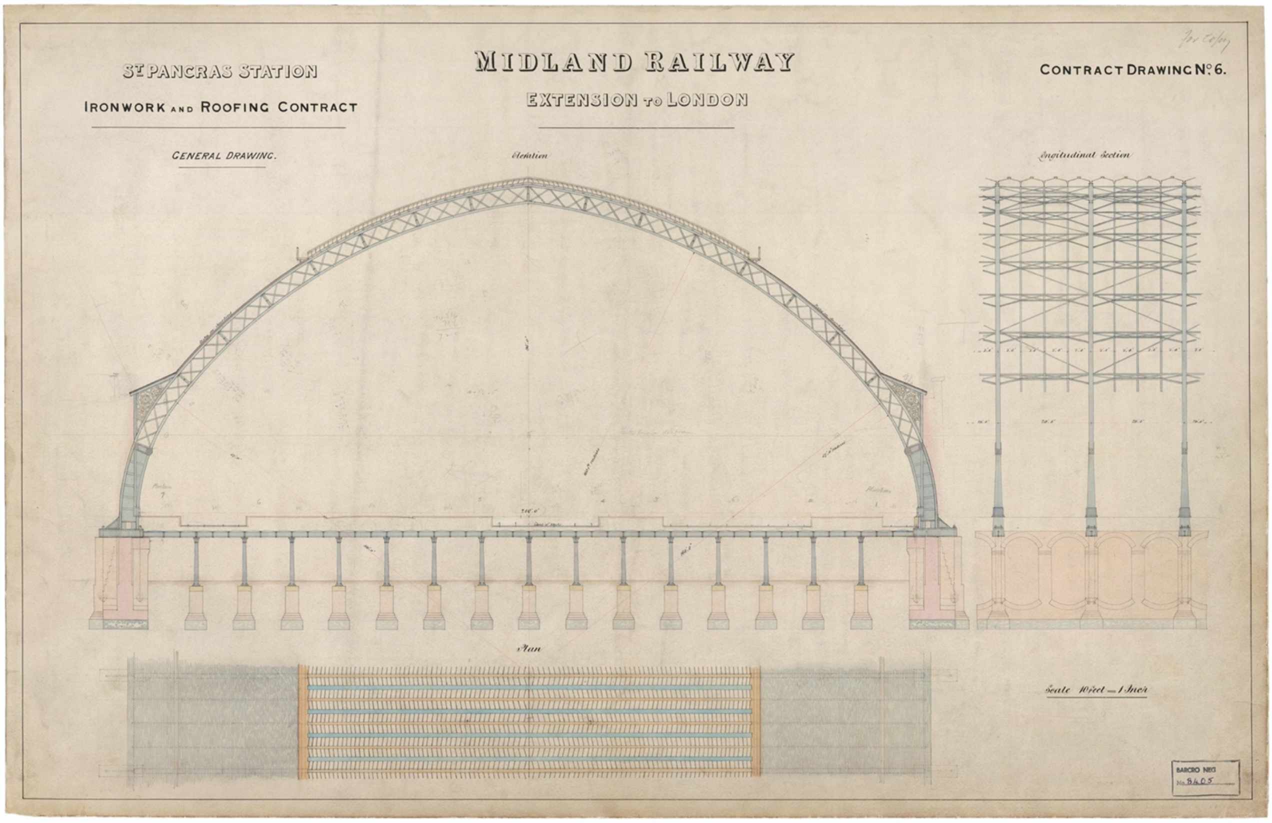


Figure 9. Section drawing of the St. Pancras Train Shed trussed arch roof (Barlow, 1868)

St Pancras Station, completed in spring of 1869, was designed by William Henry Barlow, the consulting civil engineer for Midland Railway who built the station so they could run their own route into London (Bradley, 2007).

The train deck was supported by deep cast iron girders and cast-iron columns, at appropriate spaces to store barrels of beer, a key London import for Midland Railway. The roof, formed of trussed wrought iron arched ribs, spans 75m, springing from the platform level. At the time of construction, it was the largest single span roof in the world. Outwards thrust from the arched roof is restrained by deep cast iron girders running the span of the arch underneath train deck (Barlow, 1870) (Bradley, 2007).

Aesthetic consideration was given to the arched ribs in terms of the pale blue colour proposed for them. Barlow selected this colour so that the roof would merge with the sky on a clear day (Barlow, 1870). In terms of decorative ironwork, circular iron elements were designed in the springings either side of the arched ribs as per below drawing. The limited mention of these circular elements in literature refers to them consistently as decorative pieces. Engineering judgement indicates these circular elements would however help to stiffen the structure laterally, providing a connection between the outer rafters and the arch. Figure 9 and 10 are engineering sections of the building, showing the station roof and the arch springing respectively.

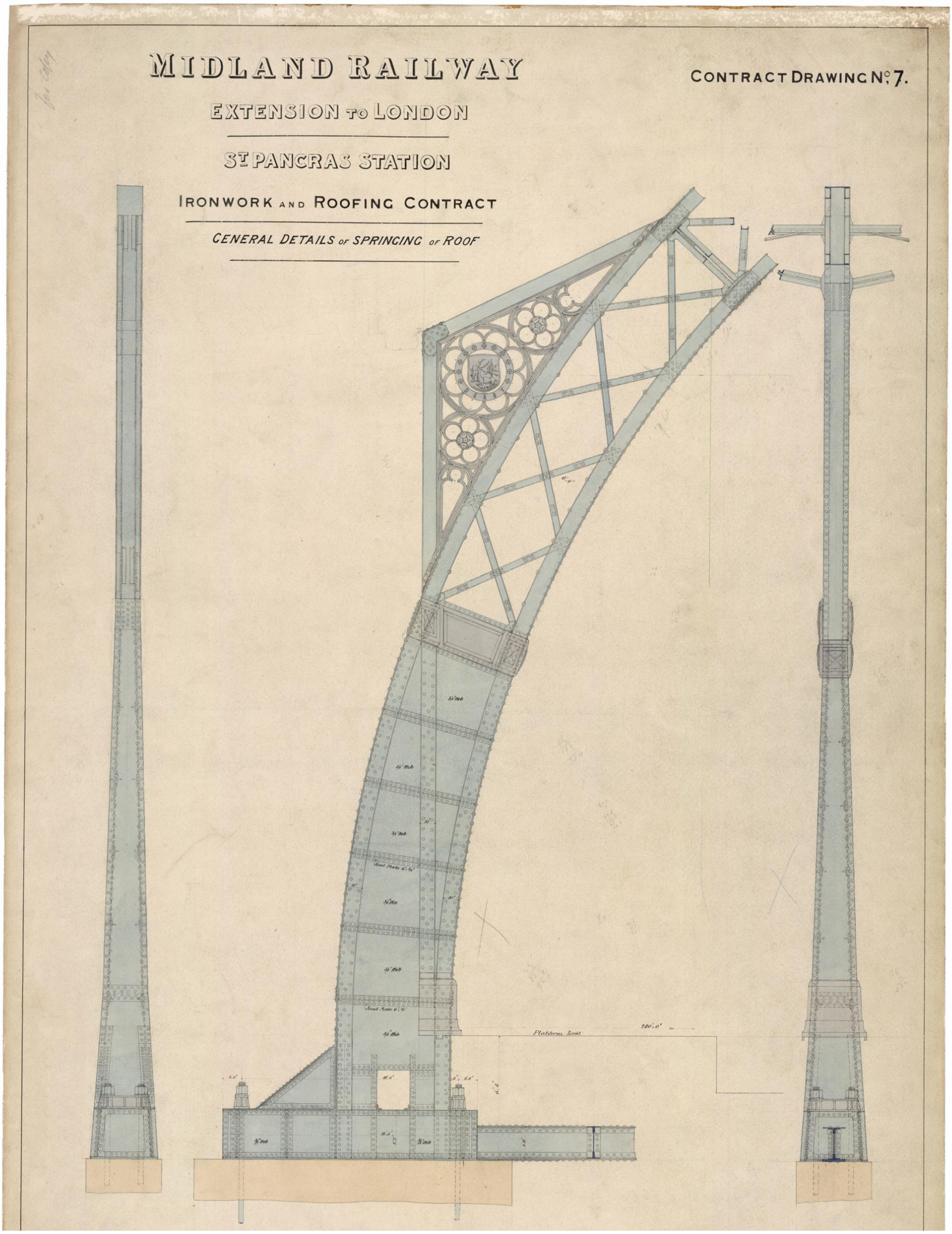


Figure 10. Section detail of the St. Pancras Train Shed arch roof springing with decorative circular spandrel plates (Barlow, 1868)

## 8. The Ardant Truss

The Ardent truss is a roof truss design comprising a ‘spandrel arch’ attached tangentially to the principal rafters and gable frame. The idea was initially conceived by French military engineer Paul-Joseph Ardant as part of works published in 1840. It is also known as the De Dion truss, named after Henri De Dion, who developed the design in 1878 (De Bouw et al, 2009 and 2015).

The design was intended as an aesthetically pleasing alternative to the Poloceau truss, a conventional truss design popular due to its optimal use of elements, minimising bending. The Polonceau truss relies on a horizontal tie-rod spanning the roof to counteract horizontal thrust caused by roof loads. This tie-rod caused the truss to be considered ugly and industrial by critics at the time. Furthermore, the tie-rod intruded on a significant volume of interior ceiling space. The Ardant truss managed to reduce horizontal thrust to similar levels of the Polonceau truss through use of extremely stiff connecting web members between the lower arch element and the principal rafters (Bouw, 2010). Figure 11 shows a comparison between the two truss configurations.

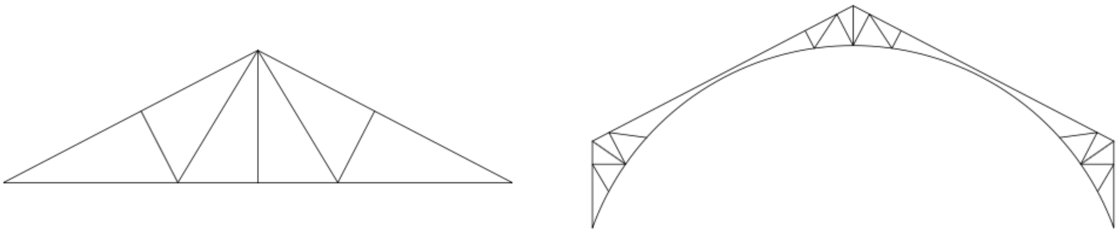
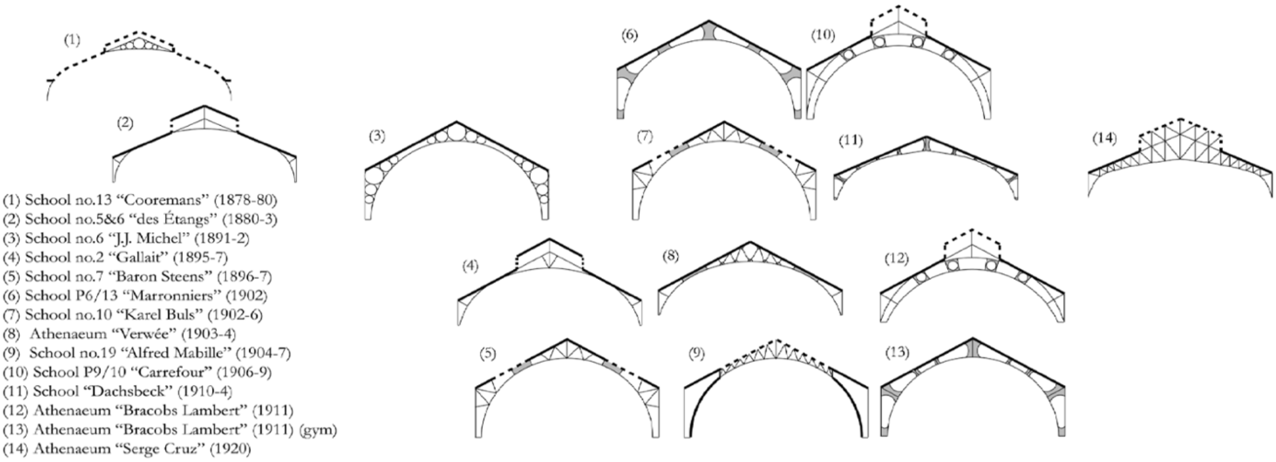


Figure 11. Indicative Polonceau truss (left) and Ardant truss (right)



(1) School no.13 “Cooremans” (1878-80)
(2) School no.5&6 “des Étangs” (1880-3)
(3) School no.6 “J.J. Michel” (1891-2)
(4) School no.2 “Gallait” (1895-7)
(5) School no.7 “Baron Steens” (1896-7)
(6) School P6/13 “Marronniers” (1902)
(7) School no.10 “Karel Buls” (1902-6)
(8) Athenaeum “Verwée” (1903-4)
(9) School no.19 “Alfred Mabille” (1904-7)
(10) School P9/10 “Carrefour” (1906-9)
(11) School “Dachsbeck” (1910-4)
(12) Athenaeum “Bracobs Lambert” (1911)
(13) Athenaeum “Bracobs Lambert” (1911) (gym)
(14) Athenaeum “Serge Cruz” (1920)

Figure 12. Basic detail of the various Ardant truss designs used for Brussel Model Schools between 1878 – 1920 (de Bouw, 2010)

The Ardant truss was used in the design of several 'Model Schools' in Belgium between 1878 and 1920. The truss design varied in each school, particularly with respect to the web members. Connecting members took the form of hoops, straight bars, trusses and gusset plates (De Bouw & Wouters, 2015). Figure 12 shows the basic design of 14 Ardant trusses used for the Belgian Model Schools.

In 1902, a prominent engineer of the time named Arthur Vierendeel published a design procedure that proved circular elements could be used to provide the stiff connections necessary for true Ardant truss.

In the design procedure, Vierendeel approaches the circular elements as though they were in fact a series of straight truss members. Each 'pseudo' straight truss member spanned from the intersection of one circular element with the arch / rafters, to the same intersections of the neighbouring circles. Vierendeel used a graphic statics approach in his calculations to determine the stresses acting along these 'pseudo' straight truss members. In reality, the stresses transferring between these two intersections would do so via an 'S' shaped path comprised of segments of the two adjacent circles. Once stresses along these paths had been determined, Vierendeel designed the circles sufficiently thick such that all the 'S' shaped paths remain safe from failing. He considers both axial forces and bending moments from the eccentric load caused by the curved path (Bouw, 2010).

Figure 13 shows Vierendeel's drawing of the Ardant truss he designed, the completed detail on the left and the preliminary detail on the right. Figure 14 demonstrates the principle Vierendeel used, showing some 'pseudo' straight truss lines in blue, and the actual curvy truss members in red.

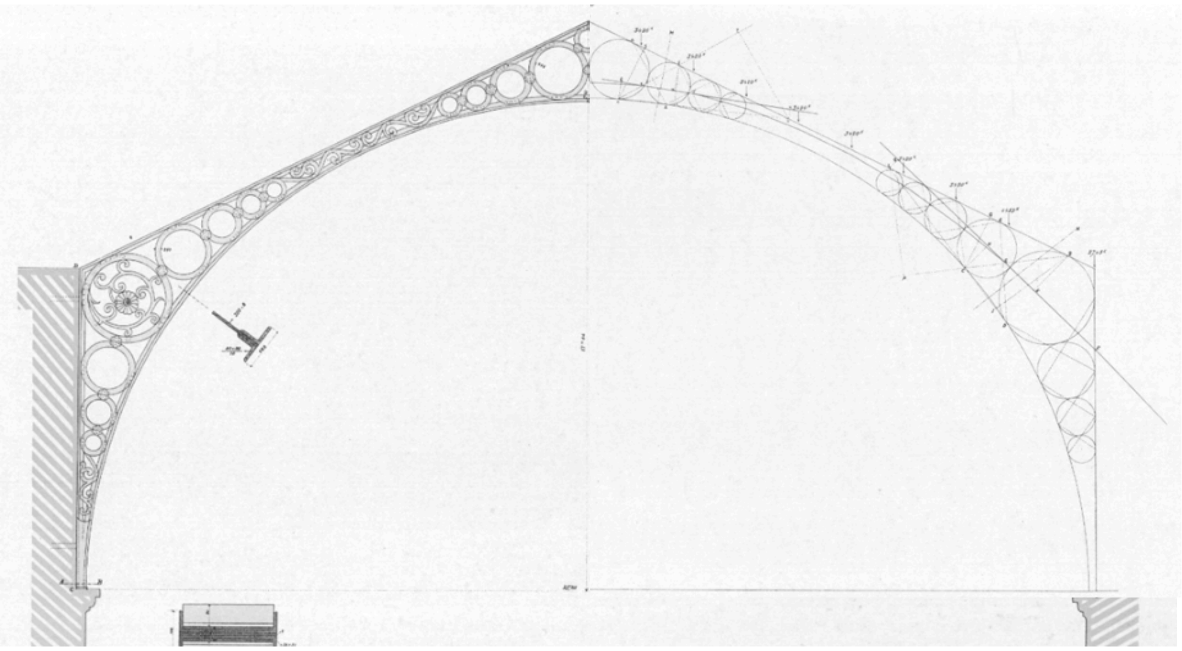


Figure 13. Vierendeel's sketches of the Ardant truss he designed with circular web members (Vierendeel, 1902)

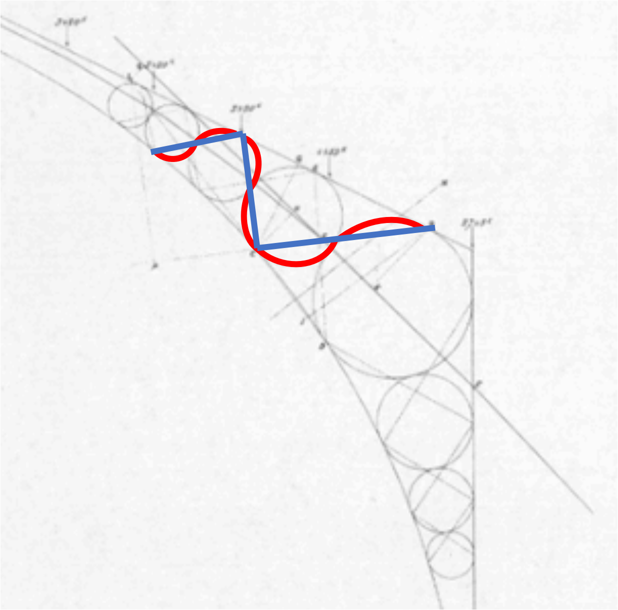


Figure 14. Mark-up of assumed straight truss members (blue) against actual curved load paths (red)

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