The Iron-Wood Composite Section of the Carrousel Bridge in Paris (1834)

Jorge Bernabeu Larena

INTRODUCTION

The *Pont du Carrousel*, built in Paris in 1834 by the engineer Antoine Rémy Polonceau, shows one of the first structure examples of combining several materials at the same section. As an early insight into the combined materials' construction and resistance possibilities, the French engineer included pine wood inside the section of the cast-iron main arches, bonded to the metal by bitumen.

The hollow iron section was used as a load-bearing element from the outset of the 19th century, although it involved certain problems: irregular thickness, execution difficulties and a deficient response to vibration requirements. To get round these problems, Polonceau proposed two cast-iron pieces joined together to form a hollow oval section, which enclosed a wooden inner filling. This aimed to reduce the arch's vibrations, facilitate the positioning of the metallic pieces and improve the weight-bearing capacity of the cast-iron elements.

On the basis of a thorough description of the work, of the tests carried out and of the designer's considerations (Polonceau 1839), this report presents a quantitative analysis of the two materials' combined response, both in service and ultimate limit states. The original supposition, that the materials act in collaboration, is demonstrated, even under the least favourable conditions of of the bitumen bond’s lack of adherence. This early application of composite resistant response involving two materials, though not followed through in its day, went beyond its creator's expectations and can now be seen in modern-day constructions of composite arches.

Figure 1. Carrousel Bridge, 1834. (Polonceau 1839, lam. I)

THE CARROUSEL BRIDGE

The Carrousel Bridge, also known as the *Pont du Saint-Pères*, was planned to cross the Seine in front of the entrances to the Louvre Museum. In the year 1831, the Seguin brothers proposed a suspended bridge, similar to their own previous designs. At Polonceau's insistence, the Public Works Ministry agreed for the tender to require a new solution. Polonceau's project had three cast-iron arches with a span of 48 m, on two piers in the river **(fig. 1)**. The most characteristic feature was its the circular rings, decreasing in diameter, which provided support for the upper deck resting on the arches.

The two solutions, the Seguin brothers' classic suspended structure and Polonceau's innovative solution with wood and iron arches, gave rise to a significant technical dispute that was brought to a Council of State. The work was adjudicated in favour of Polonceau's design on the 11th of October, 1831. Once decided, the start of construction work was to undergo a one-year delay due to doubts put forward by the *Société des Ponts des Arts* and because a new, more economic variation, was proposed. Finally, Polonceau assumed the construction costs and the foundations began to be laid in October, 1832 (Picon 1997, p. 110). With the work under way, Polonceau depleted his modest fortune and was about to abandon work when, at the last moment, he obtained the necessary funding.

Construction work came to a successful conclusion in 1834. In 1883, traffic had to be closed for six months to replace the wooden deck, which had deteriorated considerably. In 1906, the deck was replaced again, substituting the wooden parts with metal beams. The bridge remained in service until the year 1935 when, due to its deficient dynamic response to new traffic requirements, it was substituted by a new, reinforced-concrete structure.

The decreasing circular rings between arch and deck certainly stand as Polonceau's bridge's most characteristic design element. The first example of this solution was Sunderland Bridge, built in Great Britain in the year 1796 **(fig. 2)**. With a span of 72 m, the bridge proved how competitive metal structures were with respect to stone vaults, making greater spans possible at a lesser cost. The lightness and transparency of the tympanums on the iron arches took shape in Rowland Burdon's concept for Sunderland Bridge in the characteristic tangential circles, decreasing in diameter.

Other constructions, built after Carrousel Bridge, were to repeat the motif of circular rings. Among them, the Saint Thomas Bridge over the main canal in Strasbourg, Alsace **(fig. 3)**, following Polonceau's own design and still in service since 1841 (Fernández Troyano 1999, p. 331), La Mulatière Bridge in Lyon dating from 1843, now destroyed (Picon 1997, p. 110) and a small bridge on the River Lanterne in Conflans-les-Bourgignon in Haute-Saône (Picon 1997, p. 110).

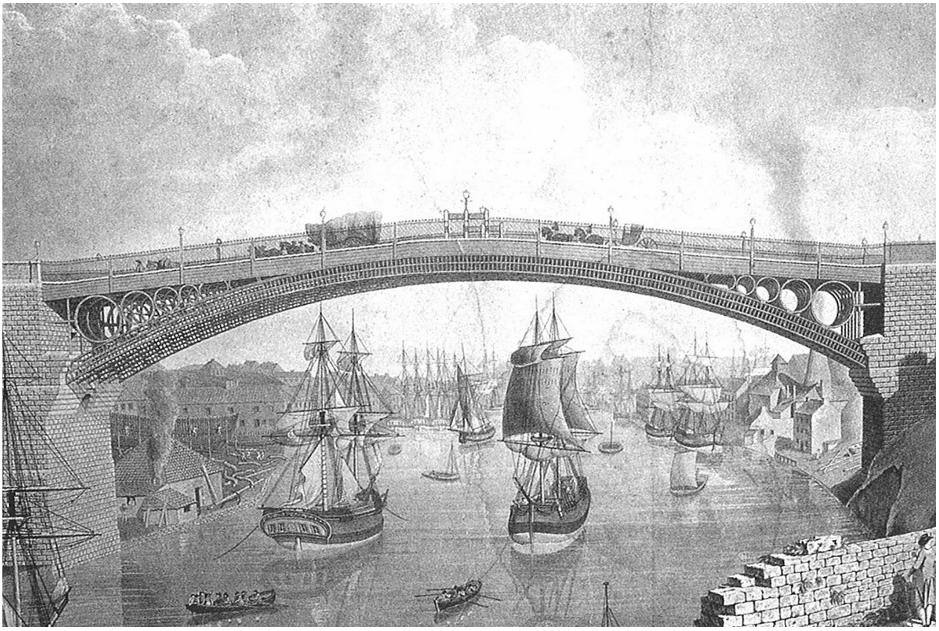

Figure 2. Sunderland Bridge, 1796. (Picon 1997, p. 490)

Figure 3. Saint Thomas Bridge, 1841. (Fernández Troyano 1999, p. 331)

An almost identical copy of the Carrousel Bridge is Triana Bridge in the Spanish city of Seville **(fig. 4)**. Designed by the French engineers Bernadet and Steinacher, the bridge crosses the River Guadalquivir by means of three arches with spans of 45 m. Built between 1845 and 1852, the bridge is still in service today and maintains its original appearance, although the deck has been substituted with a metal, load-bearing deck that crosses the spans without the need for support by the arches (Rubiato 2004, pp. 208-221).

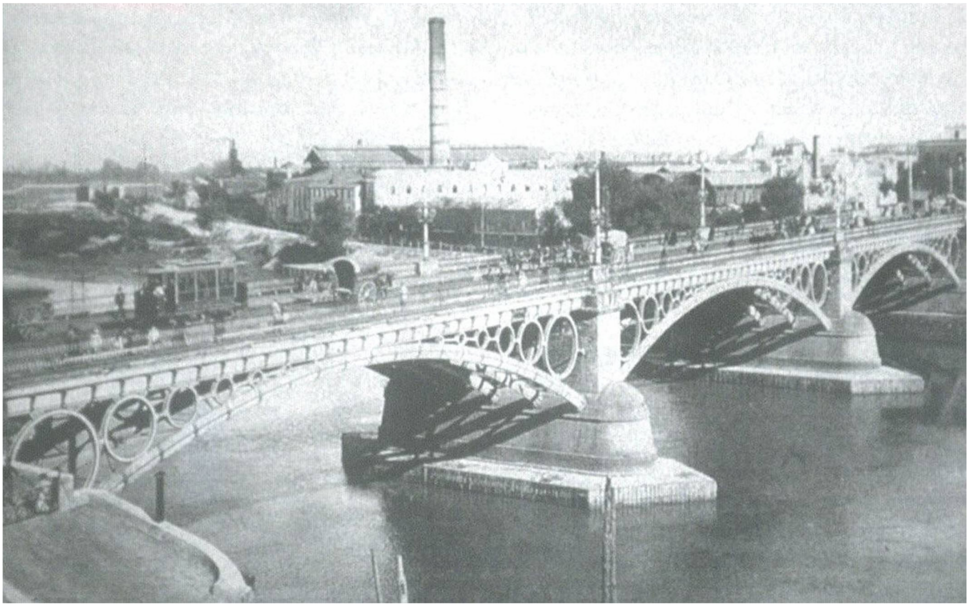

Figure 4. Triana Bridge, 1852. (Rubiato 2004, p. 210)

THE IRON-WOOD COMPOSITE SECTION

One feature of the Carrousel Bridge which was much less visible and, nevertheless, a major innovation and an absolutely unheard-of solution for its time, was the inclusion of an inner wooden core inside the hollow iron sections of the main arches.

According to Polonceau, the idea for using hollow iron sections first came from the German engineer Reichenbach, who, at the beginning of the 19th century, proposed using load-bearing, cast-iron sections similar to water-pipes, although the idea coincided in the time with publications by the Bavarian engineer Wiebeking and the Frenchman Gauthey (Polonceau 1834, pp. 5-6). Watt, on his part, had patented the hollow cast-iron column that allowed for rainwater to be evacuated from inside, rapidly generalized as a construction pillar. All these systems showed a number of difficulties in implementation and response to vibrations. Hollow parts of a certain length were often irregular in thickness.

To get round these problems, Polonceau proposed two cast-iron pieces that were joined to form a hollow, oval section, enclosing an inner, wooden filling **(fig. 5)**. The wooden core was made up of nine layers of northern pine, 55 mm thick, curved to their most flexible size and bonded by bitumen and tightening screws as if it were an single wooden piece **(fig. 6)**. The spaces between the wood and the iron were filled with bitumen to make sure that the materials were adhered together. One of Polonceau's aims was to reduce the arch's vibrations, so he also thought of filling the space with sand, plaster, mortar or concrete. But wood provided low density and a load-bearing capacity that also made it easier to position the metal pieces. As the axis of the wooden and iron sections were coincidents, the wooden core was used as a geometric calibration of the arch which the cast-iron pieces finally embraced by means of cross bolts. Additionally, the wood in turn acted as a load-bearer during the metal parts' assembly, so the wooden core itself played a role in the arch's assembly. Polonceau was aware of this resistant function of the wooden core to the extent that he trusted in the wood's capacity for occasional repairs or substitutions of the metal section.

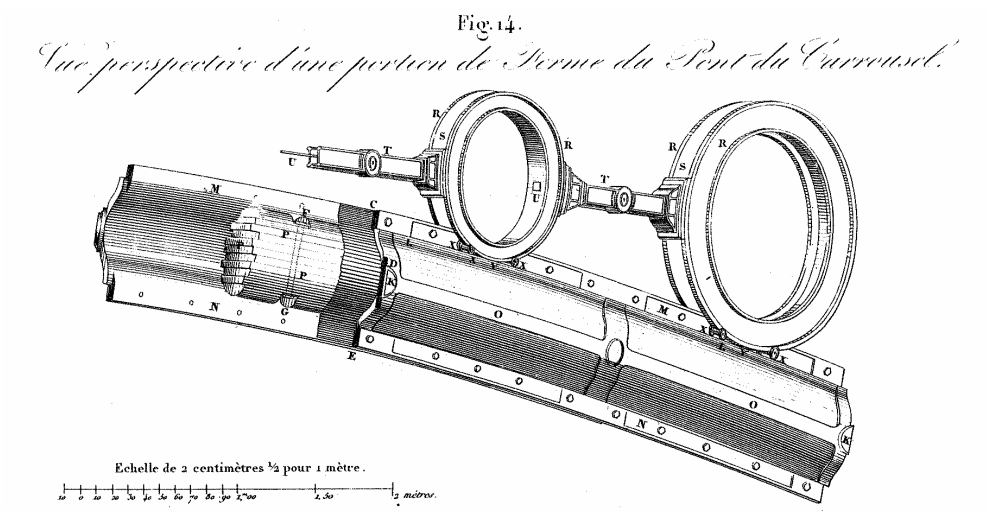

Figure 5. Carrousel Bridge, arch detail. (Polonceau 1839, lam. II, fig. 14)

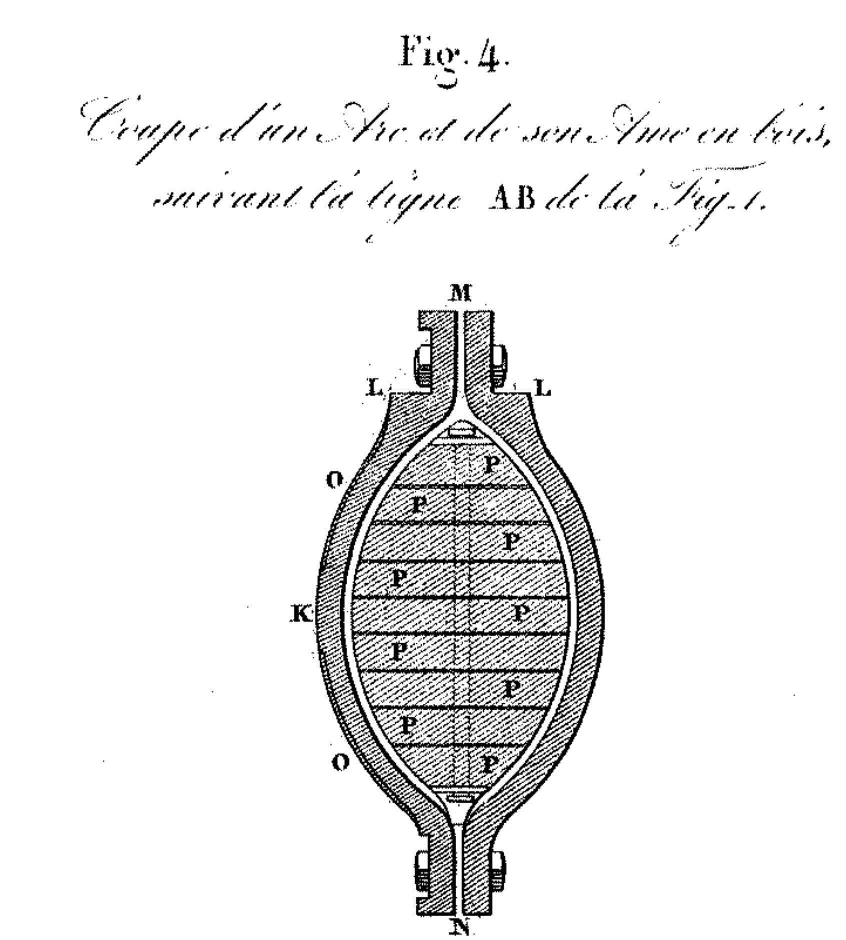

Figure 6. Carrousel Bridge, iron-wood composite section. (Polonceau 1839, lam. II, fig. 4)

Although finally never made, Polonceau designed more modest arches by reducing their centering to a wooden inner core. The wooden arch's adjustment and stabilization was to be carried out by means of a series of cables, while assembly of cast-iron pieces would be done symmetrically on each side to avoid irregularities under occasional unbalanced loads. This design took advantage of composite construction's possibilities and is linked through time with future arches of composite steel-concrete constructions at the start of the 20th century (Bernabeu 2005). What for Polonceau was an inner wooden centre enclosing the metallic section, was to become a steel centre acting together with concrete in a two-fold approach. Firstly, the load-bearing wood and the cast-iron enclosure was to be substituted by a rigid steel reinforcement embedded in concrete. Finally, in actual composite arches, the concrete acts as a filling for the surrounding steel structure.

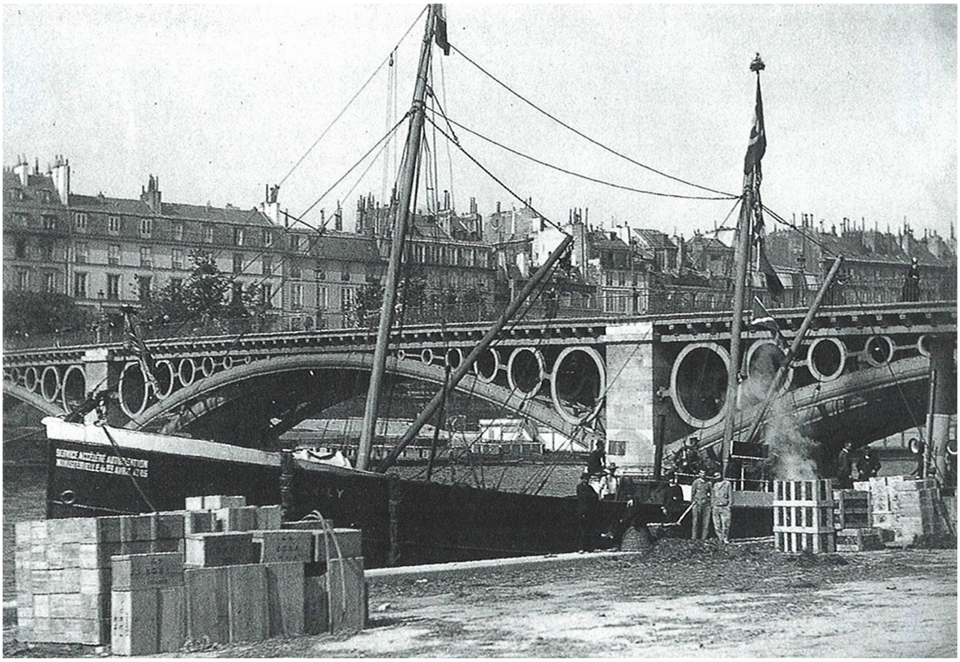

Figure 7. Carrousel Bridge. (Picon 1997, p. 109)

ANALYSIS OF THE IRON-WOOD COMPOSITE SECTION

The conception of the bridge established a significant precedent for composite construction. The French engineer described how a correct union between the two materials provided greater joint resistant behaviour than the addition of their individual properties. In an initial definition, closely adapted to the composite section, Polonceau described the combined deflection of the composite section, both in service and collapse behaviour, a state where he observed a greater combined ductility. In his own words:

> J'ai parle tout à l'heure de la résistance des arcs en bois, mais il faut remarquer que la force de résistance additionnelle qu'ils procurent aux arcs en fonte, est supérieure à leur force propre; en effet les vides qui restent entre les faces intérieures des voussoirs et les bois étant remplis complétement en bitume coulé à chaud, il y a ahérence de tous les points des surfaces extérieures des bois et des surfaces intérieures des fontes : or cette adhérence ajoute beaucoup à la somme des résistances particulières du bois et des fontes rendus par leur jonction tout à fait solidaires. La résistance totale des deux pièces unies s'accroît surtout par la différence qui existe dans la manière dont les fontes et les bois se comportent sous les charges ou sous les chocs qui tendent à les rompre. On sait que les pièces de fonte se divisent, après une légère flexion, par des simples sections brusques et transversales peu

> écartées du point de flexion ; tandis que le bois, et particulièrement les bois résineux, ne peuvent, à raison de leur élasticité, se rompre qu'après avoir pris une courbure beacoup plus prononcée, et que leur rupture se fait par arrachement irrégulier des fibres, sur une assez grande longueur. Si donc on charge à l'excès un cylindre creux en fonte, rempli exactement par un cylindre en bois plein, la fonte ne pourra prendre la flexion qui précède immédiatement sa rupture, sans faire fléchir le bois intérieur de la même manière ; mais celui-ci, opposant sa force élastique et de ressort à la pression qu'il reçoit de la fonte dans son milieu, résiste à la flexión du métal, et par là arrête et retarde sa rupture. D'un autre côté, la fonte, fortifiée par la résistance nerveuse du bois, est mois prompte à céder.
> […]
>
> On comprend d'ailleurs facilement qu'independamment de la résistence additionnelle des bois insérés dans les cylindres de fonte, du moment que le fer et la fonte sont liés, au moyen du bitume, par tous les ponts des surfaces contiguës, le bois, qui de sa nature est trop flexible, se trouve fortifié par la rigidité de la fonte, et qu'en même temps, son élasticité vient au secours du métal qui n'en a point assez, et remédie à sa sécheresse et à sa fragilité.
>
> (Polonceau 1839, pp. 35-36)

Below, we analyse the real response of iron-wood's composite section in a two-fold approach:

- Behaviour before collapse, on the basis the tests carried out by Polonceau himself and recorded in (Polonceau 1839, note E, p. 103).
- The elastic response of the arch with a structural matrix model.

Ductile behaviour before collapse

To verify these effects, Polonceau carried out a series of tests on composite iron-wood sections under increasing loads up to break-point. These tests, carried out with 1 m-long cast-iron hollow tubes, 6 cm in external diameter and 5 mm thick, with a wooden core, showed greater deformation capacity of the composite sections before breakage, plus greater ultimate load.

> Pour me rendre compte de l'acroissement de résistance que l'on peut donner à des cylindres en fonte, en garnissant leur intérieur en bois, j'ai fait des épreuves sur quatre tubes, dont deux en fonte dure et les deux autres en fonte douce. Ils avaient chacun 1 mètre de longeur, un diamètre extérieur de 6 centimètres et une épaisseur moyenne de 5 milimètres. J'ai inséré dans deux de ces tubes, des cylindres de bois enduits de bitume avant leur introduction, mais la jonction de la fonte et du bois a été fort imparfaite à cause des irregularités de l'intérieur des tubes et de l'impossibilité de couler du bitume dans des intervalles aussi étroits.
>
> (Polonceau 1839, p. 103)

The test results are summarised in **(table 1)**. The chart is completed with the break stresses in each partial section, iron (i) and wood (w), for the respective areas obtained as of the description of the test tube sizes: A_i= 8,64 cm^2; A_w= 18 cm^2.

Table 1. Polonceau's test results, information derived from (Polonceau 1839, note E)

	Chilled Iron		**Soft Cast Iron**	
	Iron	**Iron-Wood**	**Iron**	**Iron-Wood**
N_u (kg)	680	1040	1080	1450
$\square_u$ (mm)	6	8	10	12
$\square_{i\,u}$ (kg/cm^2)	78.7	78.7	125.0	125.0
$\square_{w\,u}$ (kg/cm^2)	-	20.0	-	20.0

From the test, Polonceau concluded that the wooden core increased the resistance of the pieces:

> Ces expériences ne sont assurement pas suffisant pour établir des rapports exacts, parce qu'elles n'ont pas été assez variées, que les tubes étaient trop petits, et qu'en outre leur épaisseurs n'étaient pas perfaitment uniformes ; mais bien que très incomplètes, elles suffisent pour prover que l'insertion d'âmes en bois dans des tubes de fonte augmente sensiblement leur résistance.
>
> (Polonceau 1839, p. 103)

In fact, it was shown that wood contributes its own ultimate capacity to the composite section, increasing the breaking load of the test tubes. However, the fundamental contribution of the wooden core in the cast-iron tubes was that it allowed for increased strain. Wood does not increase the load-bearing properties of metal but it does increase its strain capacity up to break-point.

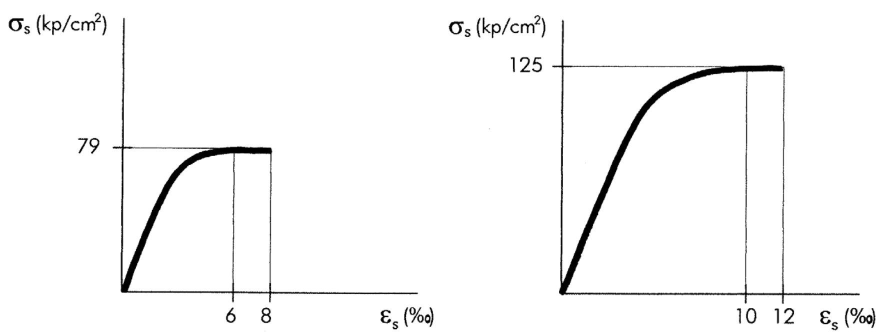

Figure 8. Stress-strain behaviour based on Polonceau's test.

If we represent these results in a stress-strain diagram **(fig. 8)** we can see that the wood improves the strain response of these first cast irons. The graphs aim to resemble the characteristics of modern-day steels and refer to the response of composite steel-concrete sections (Martínez Calzón 1978, 277). In this case, it is not that the wooden core prevents the local buckling of the section's thin metal plates, it merely accompanies the metal up to breakpoint, allowing for greater displacement. Ductility, the capacity to deform before breaking, is one of the factors that improves structure safety.

Composite action in the arch

In the behaviour of the bridge in service, there may be some doubt as to the effectiveness of bitumen in transmitting the shear forces in the connection between iron and wood. In evaluating the real effectiveness of the combined materials, an iron-wood arch model is proposed.

The theory of composite construction was defined after the Second World War and one of the main reference works is the significant theoretical work by Sattler. For our analysis, we shall use this for the definition of an "ideal section" based on the relationships between different materials' elasticity modules:

$$n_{\square} = E_e / E_{\square} \qquad \text{(Sattler 1953, 4)}$$

It is difficult to specify the characteristics of the materials used in the Carrousel Bridge's construction. By consulting different specialized manuals, we can obtain the following ranges of values:

- Cast Iron (Alamán 1990, p. 80; Martínez-Val 2000, p. 1267): $E_i = 1.05 \cdot 10^5 - 1.72 \cdot 10^5$ N/mm^2

- Northern Pine Wood (Arguelles 2000, pp. 47-49; Arredondo 1992, p. 34; Martínez-Val 2000, p. 1267): $E_w = 1.0 \cdot 10^4 - 1.5 \cdot 10^4$ N/mm^2

The arch is discretised by means of a polygonal line with nodes sufficiently close together **(fig. 10)**. Between every two nodes, two different bars are arranged, one reproducing the iron section and the other reproducing the wooden inner core **(fig. 9)**. Both bars share coinciding nodes. The performance of iron and wood is thus made independent in the whole arch and they are mutually connected in the nodes. The main aspect of the model is the linking that takes place in the nodes between the bars. If, as we propose, we do without the bitumen adherence, the only connection we must define is that of the compatibility of displacements in the normal directions to the arch. That is, in our model, wood and iron can move independently in an axial direction, but their displacement will be identical in a perpendicular direction as the wooden core cannot be separated from the iron segments. Only at the bases of the arch, nodes 1 and 25 of the model **(fig. 10)**, all the displacements are fixed.

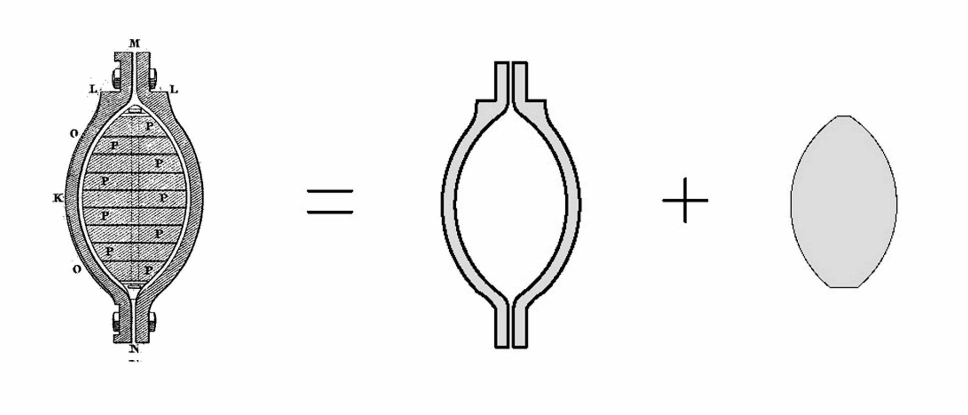

Figure 9. Carrousel Bridge, iron-wood composite section.

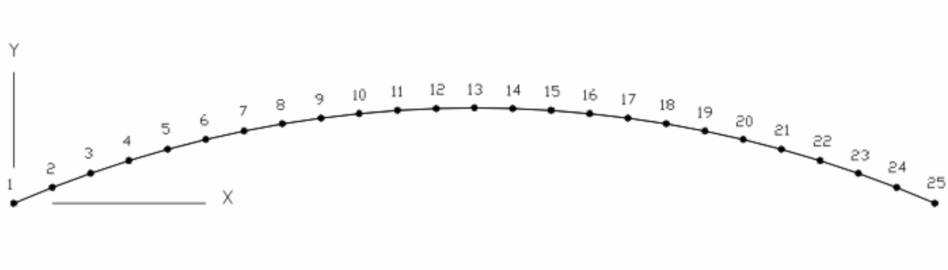

Figure 10. Carrousel Bridge, arc model.

Therefore, for our two-dimensional model, the characteristics of the partial sections are:

- Iron: A_i= 0.082 m^2; I_i= 0.054 m^4;
- Wood: A_w= 0.127 m^2; I_w= 0.0021 m^4

For the models, we adopt an intermediate value of the elastic module of cast-iron, E_i= $1.2 \cdot 10^5$ N/mm^2, and we carry out an elastic analysis under a uniform load of 20 kN/m, a guideline value of the arch's maximum service load, which comprises permanent loads and use overload. With these hypotheses, we produce three contrast models:

- Free-standing iron arch.
- Iron-wood arch with n_w= 12, a reasonable value within the ranges included in the established references.
- Iron-wood arch with n_w= 6, a value deduced from the distribution of loads at collapse obtained in **(table 1)**.

The results are summarised in **(table 2)**. The table shows the vertical deflection at mid-span, node 13, and the axial compression loads in iron and wood elements.

Table 2. Carrousel Bridge, models results.

	1	**2**	**3**
	Iron	**Iron-Wood** $n_w = 12$	**Iron-Wood** $n_w = 6$
$\square_{Y\,13}$ (mm)	-12.8	-11.4	-10.2
$N_{k\,i}$ (kN)	-1180	-1040	-920
$N_{k\,w}$ (kN)	-	-140	-260

It is clear that the wooden inner core is totally effective, even without the existence of the bitumen designed by Polonceau as connection. This means that the composite action is produced due to the action of forces in a perpendicular direction on the arc, while the shear forces do not appear. When the metal arch tries to deform and meets with the constriction of the presence of the wooden inner core, radial forces are produced, with make compatible the deformations of the iron and the wood arches **(fig. 11)**.

The effect is very different from the one produced in straight elements, where to obtain a composite response from the materials, shear stresses must take place between them and, therefore, ther must be a real connection.

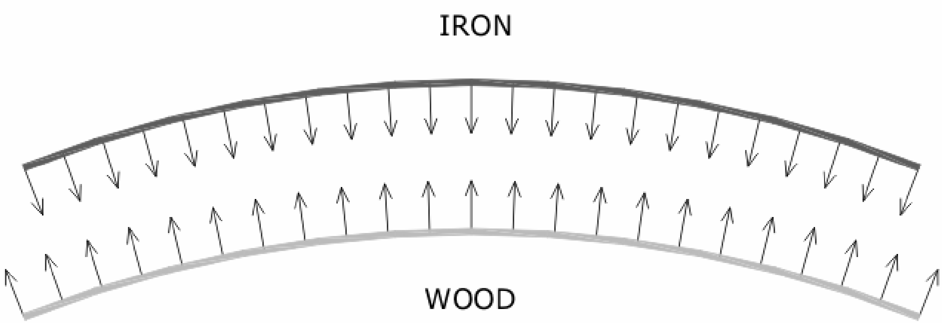

Figure 11. Carrousel bridge, deflections compatibility.

The structure's modelling has followed the criteria established for computerised analysing of composite structures in the references (GEHO 1998; Manterola 1998) and particularly the methodology laid down in (Manterola 2001). Specifically, this last reference sets forth a similar analysis to the composite action in the arch for the Escudo Bridge. The central part of the bridge is made up of two tubular arches with a span of 126.4 m **(fig. 12)**. Each arch is made up of two steel tubes, 1219 mm in external diameter. The arch is filled with mass concrete to obtain a composite structure **(fig. 13)**. There is no connection between the concrete and the steel.

Figure 12. Escudo Bridge, 2001. (Manterola 2001, p. 171)

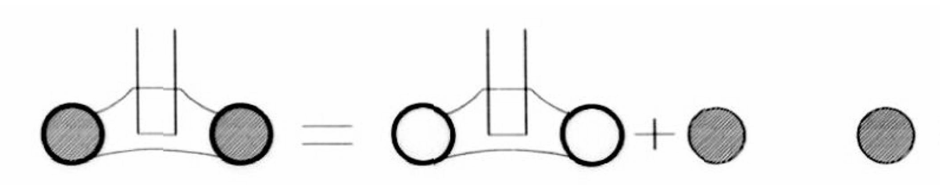

Figure 13. Escudo Bridge, steel-concrete composite section. (Manterola 2001, p. 173)

The arch model, using independent bars for steel and concrete, establishes the compatibility of deflections of both under thermal and reological loads (Manterola 2001, pp. 172-173).

Having shown the composite iron-wood action of the Carrousel Bridge, it is interesting to note the conceptual and analytic analogy with modern-day constructions of composite arches and with a time difference of almost two centuries.

CONCLUSIONS

The Carrousel Bridge, now destroyed, built in Paris in 1834, with its triple arch over the Seine and its characteristic circular tangential rings between arches and deck, stands as an icon of iron bridges and of French engineering at the beginning of the 19th century **(fig. 14)**. Its designer, A. R. Polonceau, created an original solution in the cast-iron arches. It formed the hollow oval section by two pieces of iron joined over a wooden inner core. The construction represents a major historical landmark in composite construction.

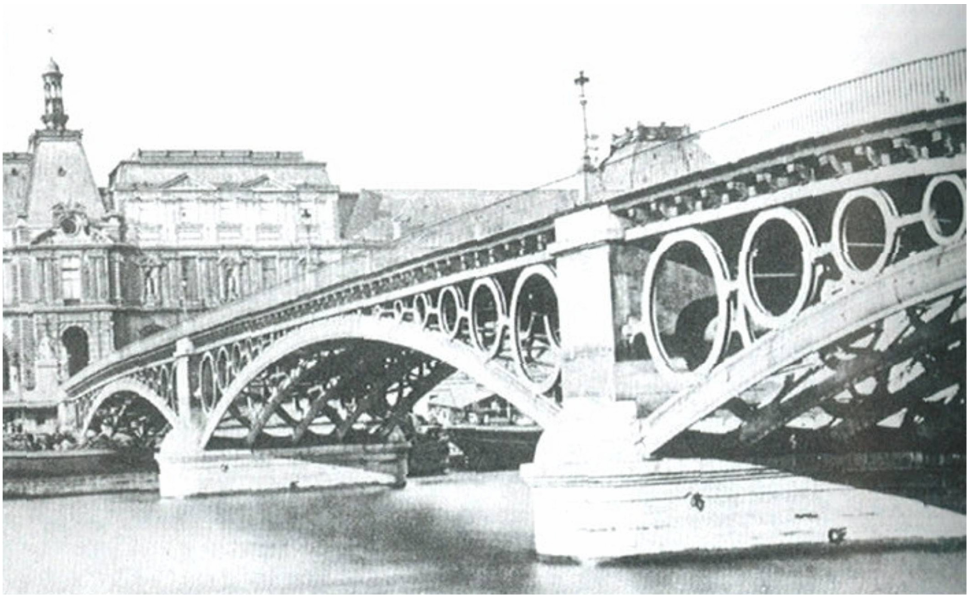

Figure 14. Carrousel Bridge. (Fernández Troyano 1999, p. 330)

The designer's insight that the collaboration between two materials, iron and wood, provided a joint resistant behaviour with greater capacity than the addition of its individual properties, is verified by analytical study.

On one hand, on the basis of the tests carried out by Polonceau himself, the section's ductile behaviour at breakage was deduced, as an antecedent to the characteristics of modern-day steels. On the other hand, a matrix model of the structure demonstrates that, even when bitumen planned by the designer as a connecting element was not effective, the deflections compatibility between the two materials ensured their composite action.

Differences apart, there are clear parallelisms between the Carrousel Bridge and modern-day constructions of composite arches. Steel has replaced iron and concrete has taken the place of the wooden inner core.

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