How stiff is a timber curved plank? Historical discussions about curved plank structures

Lydia Hahmann

In: Dunkeld, M. et al. (Ed.): Proceedings of the 2nd International Congress on Construction History, Queens´ College, Cambridge University, March 29-April 2, 2006, vol.2, pp.1501-1516. ISBN 0-7017-0205-2

The 120 foot (approximately 38 metres) wide spanning timber cupola of the halle au blé quickened interest of European engineers and architects at the end of the eighteenth century. The cupola, which was economically assembled from small, thin planks, was designed by the architects Legrand (1743-1808) and Molino (1743-1831) and erected by the carpentry-master Roubo (1739-1791). With their design the building masters acted on a structural idea from renaissance times and resurrected it again at the beginning of the nineteenth century. The two hundred year old construction methods however were almost completely forgotten. A tradition of how to build a curved plank structure properly did not develop over the time.

The curved plank cupola of the halle au blé stood up to the designs of solid stone cupolas. Its structural lightness asked emulating building masters a lot of questions; moreover forced them to think in new directions:

- On one hand they had to realise, that the laws of shape and mass of traditional European vaulting structures are not one-to-one applicable on the curved planks.
- On the other hand the recovering of the historical, light timber structure forced a competent handling of material strengths, elasticity, as well as the knowledge of load transmission within the relatively soft carpentry joints. These requirements were hardly able to be fulfilled by using the laws of material sciences and mechanics of that time. To meet these requirements causes problems even today for engineers when they are calculating still existing, often very filigree curved plank structures.

But which methods did the building masters used to guarantee structural safety 200 years ago?
The first part of this paper deals with the history of curved plank structures in Europe and the handed-down structural experiences, which provided the basis for the reintroduction of the construction method around 1800. The second part introduces the structural discussions about the curved planks at the beginning nineteenth century in Germany based on the analysis of the technical literature of that time.

Experiences with curved plank structures before 1800

The curved planks were made of two or more layers of thin timber planks, which were nailed together in a curved shape by treenails. The idea of these assembled curved timber elements was already used for centuries on the building of vaulting centrings **(fig. 2)**, waterwheels or in the shipbuilding. Completely planked, curved timber roofs covered the renaissance palaces of Vicenza and Padua. Already Leonardo da Vinci (1452-1519) had already introduced assembled, teethed curved planks in his notes, published in the Codex Atlanticus **(fig.3)**. He also researched the load bearing capacity of differently shaped arches **(fig.4)**. The Italian architectural theorist Sebastiano Serlio (1475-1554) took up the idea of the curved roof structures as well in his seventh book on architecture **(fig.5)**, which was published after his death in 1619. However beside drawings, no structural building guidance can be found in both of these works.

The French Philibert de l´Orme (1514-1577), architectural theorist and architect of the royal court of Henry II, was the first who worked more deeply on the construction of the curved plank structures in his 1561 published *"Nouvelles inventions pour bien bastir et à petits fraiz"* (l´Orme 1561) **(fig.6)**. On which experiences though, did de l´Orme base his work about curved planks?

Philibert de l´Orme was an expert of the classical works on architectural theories of his time. He undertook educational journeys in neighbouring countries, such as Italy. His architectural background was based on stone structures. In this subject he devoted himself to the geometrical aspects of stone carving of vaulted structures. He adapted his experiences from stone structures to timber structures. Compared to the stone structures, de l´Orme considered the lightness and the little horizontal shear forces at their footings the main advantage of timber structures. He abandoned the complete timber planking which was used in the Italian renaissance palaces and placed the curved planks consequently edgewise. Furthermore he introduced an interlocking joining multi-curved plank - *les liernes [Engl.: the ribs]*. He suggested using only short and rigid fixed curved planks – the shorter the planks the stronger the whole structure, provided that the joints were made rigid enough. He didn't regard the joints as weak parts at all.

De l´Orme stood up for a semicircular vaulting shape of curved plank structures. He felt absolutely confident about their load bearing capacity and granted bearing distances up to 400 metres (Ruesch 1997, p. 11)! He himself was only building curved plank structures spanning up to 19.5 metres (Meschke 1989, p. 52). What made him belief in the great stability of these structures remained unclear. He convinced his clients of the general load bearing behaviour of curved planks by public load tests. In the presence of the king he once tensed curved planks of a flat ceiling by two screws against the flooring. He screwed them down until the flooring started to lift. Because he couldn't notice a lowering of the curved planks, he called it a proof for the huge bearing capacity of his invention (Gilly 1797, p. 75). Likewise he reported loading tests on the castle La Muette **(fig.7)**. According to his statements he got throughout good results (Gilly 1797, p. 5).

The tests of de l´Orme mainly served the promotion of the curved plank structures but less the scientific research of their stability. Therefore important details of the experimental setup, cross sections of the structural members, applied forces and the strengths of the counter bearing walls remained untold. This certainly explains the high deformations, which appeared only short time after the erection of one of his testing objects - the castle La Muette (Meschke 1989, p. 82).

De l´Orme tried to spread his structural idea through publications and the forwarding of curved plank models throughout Europe. Despite these efforts the curved plank structures were not taken up in the timber work literature after the lifetime of de l´Orme. Only few curved plank structures were built in the following years. Building masters at the end of the eighteenth century could only count on de l´Ormes descriptions. As well the constructors of the halle au blé still orientated on the more than two hundred year old printings of de l´Orme.

The first German publications on the construction of the curved planks around 1800 described the construction of the cupola of the halle au blé and referred to the original documents of the inventor de l´Orme.

First theoretic considerations about the stability of the curved planks at the beginning nineteenth century in Germany

The first comprehensive, German work which dealt with the construction of curved planks was published by the architect David Gilly (1748-1808) in 1797. Beside a historical overview of the construction method the work presented a commented, German translation of de l´Orme´s essays on curved planks.

David Gilly completed his translation about the curved planks by adding his own theoretic thoughts. Also for him the curved planks remained just a lighter adaptation of rigid stone vaults. Also a close colleague of Gilly, the engineer Johann Albert Eytelwein (1764-1848) regarded the timber joints as rigid connections. He neglected bending and sagging of the joints (Ardant 1847, p VI). Elastic deformations were regarded as the results of existing pressure only (Ardant 1847, p. VI).

Gilly selected the shape of the curved planks according to the minimal resulting horizontal shear forces at their supports. He granted the gothic pointed arch shape the greatest stability and the minimal horizontal shear. Deducing from the questions of arch structures he asked for more precise theoretic investigations of existing shear forces at the supports and the definition of the places of the highest pressure (Gilly 1797 p.60). Until the mid nineteenth century engineers regarded the shape of stone arches, mainly optimised for the transmission of compression forces, as well the best shape for curved timber planks. In 1825 Johann Michael Voit (1771-1846), Bavarian royal building surveyor, like Gilly also referred to the experiences of stone structures (Voit 1825). Still Panzer (1835), Bavarian royal government building officer, and the architect Johann Andreas Romberg (1806-1868) (1850) advised to use the shape of the catenary for curved plank rafters.

Gilly propagated the structure as a very timber saving but rigid structure. Convinced of the bearing capacity of curved planks Gilly contemned the *liernes* of de l´Orme in the first years (Gilly 1801, p. 28). He even thought to weaken the curved rafters through the interlocking of the *liernes*. The curved planks should be stiffened as it was usually done in roof structures of that time by the roof hip, the gable walls, the roof battening and cross laths. In his fist publication in 1797 Gilly adopted the two hundred year old span-wide-differentiated dimensions of curved rafters given by Philibert de l´Orme. Unless he knew of the great influence of the hight of the curved rafters on their bearing capacity, he didn’t give proposals for rafter heights. Rafter heights were missing in de l´Ormes work as well.

Jacob Christian Gustav Karsten (1805), private lecturer at the Rostock Academy, published an essay on the construction of curved planks. He compared the bearing capacity of curved and linear roofs by the influence of their rising angles on the existing wind loads and the resulting compression forces. He declared roofs of parabolic shape as the strongest (Karsten 1805, p. 31). Like Gilly, Karsten referred to the material tests of Pieter von Musschenbroeck (1692-1761). The professor of physics tested the strengths of several materials in the 1730s. From the strengths Karsten deduced formulas for the calculation of the necessary height of curved planks in which the resistance contained the quadratic height of the curved planks. But Karsten regarded the single curved planks spanning between their joints only. Timber carpentry joints meant fixed joints to him. From the versed proportionality of span and bending rigidity he inferred the advantage of using many and small curved elements. On Karsten´s calculation a curved rafter got the 11-fold strength of a linear rafter (Karsten 1805, p. 77).

First practical experiences with the curved plank structures in the nineteenth century

After popularising the curved plank structure and the use of this kind of structure in several buildings it was possible to analyse their general load bearing behaviour and to correct existing deficiencies. On these experiences David Gilly completed and corrected his instructions on how to build curved planks. Already in 1801, four years after his first book on curved planks, he suggested minimal heights of curved planks of 10 inches (26.2 centimetres) (Gilly 1801, p. 6). At the same time he heightened the necessary dimensions of width. In 1805 he spoke (Gilly 1805, p. 88) about meeting the architect Legrand in Paris. Legrand stated about the bearing behaviour of the curved planks: they behave well, but should be monitored, because they sway. In 1811 he reported (Gilly 1811, pp. 127-8) of the failure of several curved plank structures after heavy windstorms. He traced them back to unfavourable shapes of the curved planks, insufficient stiffening and a lack of carpentry skills. He described typical appearances of the curved plank deformations such as bulging **(fig. 8)** and lateral evasion **(fig. 9)**. On the basis of these observations Gilly retracted his earlier statements about disregarding the *lierne* stiffening of de l´Orme and advised to attach additional lateral stiffening of cogged beams and tension rods against bulging (Gilly 1811, p. 131].

The German technical literature also published critical statements of the French architect Rondelet (1743-1829). Already in 1805 he demurred about the bearing capacity of the curved planks (Gilly 1805, p. 88). According to him they lose their stability in structures spanning more than ten metres. Rondelet recognised the stability constituting elasticity of the curved planks. He explained that an assembled beam made of many small elements is not able to get the bearing capacity of a solid beam. Wider spans would therefore need very large, hardly purchasable plank cross sections. Even the halle au blé was only possible to erect by the use of many very strong planks. By considering this aspect the halle au blé could not at all be called a timber saving structure.

Franz Xaver Johann Maschek, a student of the mathematics and statics professor Franz Joseph Ritter von Gerstner (1756-1832), worked on the analysis of bearing capacity of curved plank bridges, which were shaped according to the thrust line. He criticised the stability of the plank-joints (Maschek 1843,

p. 92). He explained the lack of stability in the joints by the contraction of planks caused by existing compression forces. The arches differ from the thrust line by the resulting deformations, which according to Maschek cause the failure of existing structures. He suggested pre-compressing the thrust line shaped planks which shall be used in bridge structures before their usage (Maschek 1843, p. 135).

Curved plank assessments on load tests at the beginning nineteenth century

Already David Gilly reported a load test of a 60 feet (18,84 metres) long, 7 feet (2.2 metres) high and 2 inch (5.2 centimetres) curved plank arch which was made of two layers of planks (Gilly 1800a, p. 134). Under the load of the roofing the roof deformations were not measurable. After these results King Friedrich Wilhelm III issued the command to repeat the load test on a bridge of same length and 20 feet (6.28 metres) width which consists of 5 curved plank arches. Details of these tests were not published.

Franz Ernst Theodor Funk, hydraulic engineer of the kingdom Westphalen: Funk had erected the 6 spans and 96 metres long Weser bridge Bunte Bruecke near Minden in 1800 **(fig. 10)**. After twelve years he re-analysed the structural behaviour of the bridge again (Funk 1812). Until 1812 the bridge did not develop any deficiencies. After describing the structure of the bridge in detail he thought of the loads, which it had carried over its years of existence. In this connection he discussed the general state of structural calculation of curved planks. From his discontent of the common structural approaches he concluded, that the bending strength of curved planks can only be found by load tests. Therefore Funk tested two curved planks to obtain their absolute bearing capacity. The two curved planks followed the shape of the bridge girders and were built in the scale of 1 inch to 1 foot. He published the description and analysis of his tests in a publication (Funk 1812). The two curved planks of the model were placed 24 inches (57 centimetres) apart from each other. They were connected by cogged boards. The curved plank rafter footings were fixed in abutments. Loads were placed on the peaks of the two rafters and raised till breakage in 21 steps. The deformations under increasing loads were surveyed. The curved rafters always failed in their joints. Therefore Funk proposed strengthening the joints of the curved plank rafters by additional planks. The analysis of the tests allowed Funk to criticise the statements of Karsten about the bearing capacity of the assembled curved planks. Funk converted his results of the model tests on real structures by using the proposals of the professor in mathematics Johann Spaeth (1759-1842). Spaeth worked on the statics of timber arch bridges and analysed several material tests in 1811 (Spaeth 1811). He gave proposals how to convert results of model tests on real structures on the basis of the resulting stresses. By assessing an existing structure, the precise analysis of existing loads and additional model tests Funk was the first, who not only tried to prove safety for a single built structure but to give others a detailed basis for similar curved plank rafter assessment. Funk advised to take a 3.4-fold safety to the ultimate loads (Funk 1812, p.33).

Zimmermann, building officer of Lippstadt, criticised Funk´s analysis, particularly his deficient documentation (Zimmermann 1830). Before he built a curved plank structure by himself, he tested models of 0.5 inch to 1foot scale. He tested five single standing arches with centre angles between 40° and 60° as well as two arches, which were connected with each other. The rafters got fixed supports. Seven ropes were fixed above the axis of the arches. The ropes carried a hanging board. Sandboxes and single loads were equally distributed on the board. The total elasticity of a curved plank structure was tested by a single load in the peak of one of the two connected arches. He measured the deflexion of the peak by the help of a rope which was tangent to the arch peak. The measurement had a accuracy of 1/16 inch. The curved planks always failed in the lower joints **(fig.11)**. The timber elements itself never broke. That's why Zimmermann asked for the strengthening of the supports of the curved rafter by using bigger cross sections. For loads more than 2/3 of the ultimate loads the curved rafters needed lateral support. This confirmed the low lateral stiffness of the curved planks, which was also one of the main problems of the deficiently stiffened curved timber roofs. Zimmermann recorded the deformation behaviour until failure in detail. He detected the more elastic structural behaviour of the curved planks compared to stone arches and compared it to the behaviour of iron screwed frames or tubes. He recommended using a safety of 5 for the ultimate loads. He attested the Bunte Bruecke built by Funk after 30 years of existence still a good stability.

In 1840, the French engineer and professor of the art of building and construction at the engineering and military school in Metz, Paul Joseph Ardant (1800-1858) analysed common strutted frames and timber arch structures. By building the timber arches in de l´Ormes manner he already recognised their great flexibility. After these experiences he strict distinguished the behaviour of stone arches from iron or timber arches. Furthermore he recognised the great influence of the strength and the number of joining elements on the bearing capacity of curved planks. By analysing already existing test results he emphasised that it is not enough to find the ultimate loads of the tested elements. According to him the bending should be more deeply regarded.

Ardant analysed the deformation of arches on small scale models made of solid timber elements. The results of the performance of the arches under different loads laid the basis for further load bearing tests on full scale models. Additionally he determined the coefficient of elasticity on fir timber prism of 7 centimetre lengths. The large scale models of curved and linear rafters had spans of 12.03 metres. The arches were saved against lateral bending. In addition to general results about bearing capacity and elasticity of the curved planks, the tests objectives were to gain exact results on the resulting thrust forces at the supports. For determining the thrust forces Ardant adapted a principle which Leonardo da Vinci already used for his researches on the horizontal thrust of arches and vaults **(fig. 12)**. He applied cast iron rolls, which were mounted on rails. The arch bearings were held in position by changeable loads on rope rolls **(fig. 13)**. The necessary loads placed on the rope rolls indicated the existing thrust forces.

Ardant was the first, who used the theory of elasticity of Henri Navier (1785-1836) in the analysis of curved plank arches. He gave a basis for calculation and dimensioning of curved planks, which resulted from the statics of linear rafters. He recognised that the assembled curved planks had only half of the bending resistance of curved solid timber elements of the same length and curve. The ultimate strength was even lower. For the additional safety factor he distinguished between short time existing and long time existing structures. Short time timber structures might be loaded up to ¼ and long time existing structures up to 1/8 of their ultimate strength.

In 1847 the works of Ardant were published in German language (Ardant 1847). The disastrous results about the bearing capacity of curved planks spread quickly among the architects and engineers and commenced the decline of the curved plank structures. In the following years only some curved plank structures were erected in Germany. But still 20 years after Ardant´s publication load tests were used to solve structural questions about these structures, as the erection of the 12 metre spanning curved plank roof of the bourse of the Berlin cattle-market showed **(fig. 14)**.

Conclusion

The German building masters adopted the curved plank structure at the beginning nineteenth century. The curved structures were very attractive because of their propagated timber saving aspect. However abilities in mechanics and the knowledge of material strengths were not developed deeply enough to qualify engineers in determining bearing capacities in theoretic ways only. The structure was not traditionally grown. Therefore the basis of the construction of curved plank roofs at the beginning nineteenth century was still the two hundred year old work of the French architect Philibert de l´Orme. Throughout the first theoretical publications in Germany curved planks were regarded as almost rigid arch structures. Aspects of elasticity were totally neglected. Therefore experiences of the stone vaults were adopted for the timber structures. Questions from stone arch building, such as the ideal shape of the arches and the resulting bearing reactions, dominated the first discussion on curved planks. Only observations on the first real existing structures obviously showed the more elastic behaviour, of which timber arches are distinct from stone arches. After first cases of failure also aspects of stiffness and stiffening became more important to the building masters. Besides load tests after the erection of new curved plank structures model tests were used to gain information on the bearing capacity of the assembled structural elements. It took German building masters half a century to recognise the different behaviour of timber curved planks from stone arches and to gain safe results on the existing stresses. The realisation of the elasticity of the curved planks was the starting signal for their decline.

References:

Ardant, P J, 1847. *Theoretisch-praktische Abhandlung über Anordnung und Construction der Sprengwerke von grosser Spannweite mit besonderer Beziehung auf Dach- und Brücken-Constructionen aus geraden Theilen, aus Bögen, oder aus der Verbindung beider für praktische Baumeister so wie für Vorträge über Ingenieur-Mechanik*, Hannover: Hahn

ARGE Hochofenhalle, 2002. *Hochofenhalle des Hüttenwerkes Peitz. Aufnahme Sommer 2002. Ergebnisbericht* (unpublished report)

de l´Orme, P, 1561. *Traités de l´Architecture: Premier Tome de l´Architecture: Nouvelles inventions pour bien bastir et à petits fraiz,* Paris

Funk, F E T, 1812. *Abhandlung über die vorzügliche Anwendbarkeit der Bohlenbogen zu hölzernern Brücken, die große Öffnungen überspannen*, Rinteln: Steuber

Gilly, D, 1797. *Ueber Erfindung, Construction und Vortheile der Bohlen-Dächer mit besonderer Rücksicht auf die Urschrift ihres Erfinders*, Berlin: Friedrich Vieweg

Gilly, D, 1800a. "Etwas über Bohlendächer", *Sammlung nützlicher Aufsätze und Nachrichten die Baukunst betreffend*, part one, pp.133-8

Gilly, D, 1800b. "Etwas über Bohlendächer", *Sammlung nützlicher Aufsätze und Nachrichten die Baukunst betreffend*, part two, pp. 133-5

Gilly, D, 1801. *Anleitung zur Anwendung der Bohlen-Dächer bey ökonomischen Gebäuden und insonderheit bey den Scheunen*, Berlin: Georg Decker

Gilly.D, 1805. "Ueber die Wiedererbauung der Kuppel der sogenannten Halle-au-bled in Paris", *Sammlungen nützlicher Aufsätze die Baukunst betreffend*, part two, pp. 77-91

Gilly, D, 1811. *Handbuch der Landbaukunst vorzüglich in Rücksicht auf die Construction der Wohn- und Wirthschaftsgebäude für anstehende Cameral-Baumeister und Oeconomen*, part three, Berlin: Rengersche Buchhandlung

Karsten, J C G, 1805. *Anwendbarkeit und Construction des Bohlendaches theoretisch und praktisch untersucht auch mit Rückblicken auf die Geschichte desselben versehen*. Berlin: Heinrich Frölich

Krafft, J C, 1805. *Plans, coupes et élévations des diverses productions de l´art de la charpente, éxécutées tant en France que dans les pays étrangere*, part two, Paris and Stasbourg

Leupold, J, 1726. *Theatrum Pontificale oder Schauplatz der Brücken und Brücken-Baues*, Leipzig: Christoph Zunkel

Maschek, F X J, 1843. *Neue Theorie des Holzbrücken-Baues nach Modellen, der zufolge sich für alle Spannweiten die Tragfähigkeit der Brücken aus Versuchen an Modellen mit genügender Sicherheit ergibt*, Prag: Gottlieb Haase Söhne

Meschke, H J,1889. "Baukunst und –technik der hölzernen Wölbkonstruktionen – Vom Bogentragwerk zum Stabnetzwerk" published PhD, TH Aachen

Orth, A, 1872. "Der neue Berliner Viehmarkt nebst Schlachthaus-Anlage", *Zeitschrift für Bauwesen*. pp. 22-38

Panzer, C, 1835. *Taschenbuch für gebildete Baumeister*, München: Joh. Lindauer´sche Buchhandlung

Pedretti, C, 1980. *Leonardo da Vinci Architekt*. Stuttgart and Zürich: Belser Verlag Stuttgart

Reti, L, 1996. *Leonardo Künstler-Forscher-Magier*. Köln: Parkland Verlag

Röder, G L A, 1821. *Practische Darstellung der Brückenbaukunde nach ihrem ganzen Umfange in zwey Theilen.* part two, Darmstadt: Johann Wilhelm Heyer

Romberg, J A, 1850. *Die Zimmerwerks-Baukunst in allen ihren Theilen*, Glogau: Carl Flemming

Ruesch, E, 1997. *Baukonstruktion zwischen Innovation und Scheitern: Verona, Langhans, Gilly und die Bohlendächer um 1800*. Petersberg: Imhof

Serlio, S, 2001. *Sebastiano Serlio on Architecture, Volume Two, Books VI-VII of „Tutte l´opere d´Architettura et Prospetiva*, New Haven and London: Yale University Press

Spaeth, J L, 1811. *Statik der hölzernen Bogenbrücken nach der Construction des Königlich Bairischen Geheimen Raths und General-Direktors des Wasser-Brücken und Straßen-Baues Herrn Carl Friedrich von Wiebeking*, Munich: Fleischmann´sche Buchhandlung

Voit, J M, 1825. *Über die Anwendung der Curven von Holz und Guseisen zu Dächern und Brücken oder gründliche Anleitung zur Construction der Bohlendächer, Bohlenbrücken, eiserner Brücken und Dachstühle*. Augsburg and Leipzig: Jenisch und Stagesche Buchhandlung

Zimmermann, 1830. "Bemerkungen über das Tragvermögen der Bögen aus eichenen Bohlen und über ihre Anwendung zu Brücken, nach Versuchen", *Crelle´s Journal der Baukunst*, volume four, pp.367-395

Figures:

Figure 1. Timber roof structure of the halle au blé (Krafft 1805, plate 71)
Figure 2. Curved planks in vaulting centring (Leupold 1726, tab. 18)
Figure 3. Toothed curved rafters designed by Leonardo da Vinci (Reti 1996, p. 267)
Figure 4. Structural studies of Leonardo (Reti 1996, p. 213-4)
Figure 5. Timber trusses of Serlio (Serlio 2001, p. 349)
Figure 6. Curved plank structure of de l´Orme (de l´Orme 1561, p.286)
Figure 7. Roof structure of La Muette (de l´Orme 1561, p.293)
Figure 8. Typical bulging of curved plank structures (Ruesch 1997, fig. 13)
Figure 9. Typical lateral evasion of curved plank structures (ARGE Hochofenhalle 2002)
Figure 10. Bunte Bruecke built by Funk (Funk 1812, fig. 1)