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Structural Interpretation of "Armate Travi" in N-E Italy through the Historical Treatises

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Abstract The study compares ancient composite beams, located in northen Italy, with the models drawn in Treatises from XVI century to XIX century in order to define structural characteristcs of this tecnology.

Keywords: Composite beam, wooden floor, historical treaty

Introduction

The study aims to clarify the geometrical configuration and the behaviour of a particular typology of wooden beams. Historically double framework wooden floors have covered wide rooms or loggias; frequently the principal beams were made up of more wooden elements assembled together to reach considerable length. The technology of «trave armata» allows to cover large spaces – up to 12/16 meters – by using small, shaped assembled and vertical nailed elements in order to obtain a single beam. This technology spread over a large area in northern Italy between XV and XVI centuries. There are a lot of examples in buildings (palaces, castles, loggias) along the Adige's path, in Trento, Verona, Mantova and Ferrara (Badalini and Dandria 2009), but also in the large area among Emilia and Lombardia and other singular cases in Firenze.

Others examples of composite beams were studied in Provence (Bouticourt 2008) and some indications suggest an extention of this technology further the entire alpine arch. In addition the european historical treatises confirm that this method was internationally known.

In spite of they are quite common, this kind of structures hasn't been investigate in a specific way, except for the F.E.M. analisys applied in Ferrara for reconstructing the distribution of stress end strains (Fabbri 2005), and it hasn't been elaborated an appropriate calculation procedure to verify the structure. The aim of this study is to connect together the geometrical and dimensional data come from the detailed surveys of most significant floors with the informations derived from treatises in order to comprehend the assembling procedure, the role of geometrical and static characteristics and to evaluate them.

Technological Aspects

With this technology the full span elements have a section smaller than required by a single beam so it's possible to exploit the full length of the trunk with a significant material and economic savings. Setting up a composite beam requires great manual abilities by the carpenters in order to make perfect joints and also knowledge about use of 1/3 or 1/4 width/height ratio, which is the best solution for flexure strength. The assembling procedures could be little different but, typically, the beams are built in three or four pieces: the "catena", tie beam, is the only full-span element, is set in the lower side and is tensile resistant; the "puntone", two for each beam, is set above the tiebeam and is compression resistant. In the four pieces kind, a "tassello" or key are set on the centre, above the catena and between the rafters. Structural elements are joined by teeth, which form a jagged profile know as "dardo di Giove", Jupiter trait, in order to avoid the sliding.

Often tiebeam has a slight inflection upwards at the middle and finishing elements, named shoulders, were set above the rafters to regularize the top of the beam.

Long nails, close to joints, are inserted on top and hammered in again on the bottom or the contrary; in the two cases you can see on the bottom the end of the nails bended or the head that becomes an hanging bosses with also ornamental function.

The most used type is the three pieces composite beam, but when the span is more than 9 metres are employed the four pieces beam. The studied cases, in Veneto and Lombardia, rarely go over 12 metres.

Data From Studied Cases From the surveys of ten structures (Fig. 1), in Mantova and Verona, results these dimensional proportions related to the elements:
-1/3 or 1/4 width/height ratio for the beam's section
-beams in three pieces have 3 teeth (1/6 tooth's lenght/span) or 4 teeth (1/8 tooth's lenght/span) for each rafter
-beams in four pieces have 3 teeth (1/9 tooth's lenght/span) or 2 teeth (1/8 tooth's lenght/span)for each rafter, and the key 1/4 or 1/8 lenght/span. In two cases teeth have shifted position close to the heads of the beam, the place were the stress is greater.
-rafter/tiebeam height ratio varies from 5/10+5/10 to 7/10+3/10 the height of the entire beam.

Teeth could be vertical or tilted in stress direction, and nails are put at the end of every tooth.
In only one case we find a slight inflection upwards at the middle of the tiebeam. Generally this bending allowed to contain the inflection due to load during centuries.

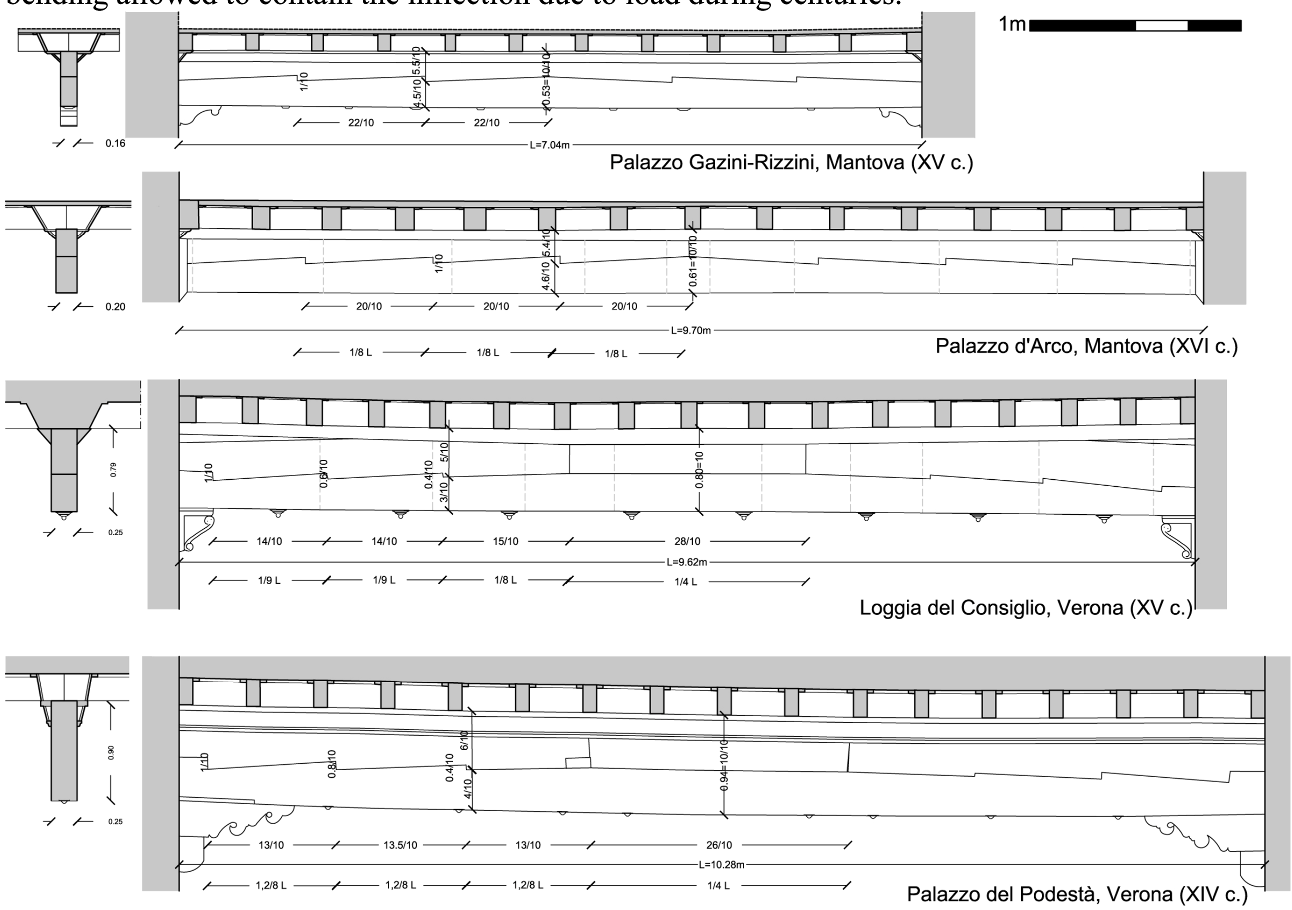

Figure 1: Some examples of ratios in the studied beams

The European Treatises from XV to XIX Centuries

Mariano di Jacopo called Taccola, in "*Liber tertius de ingeneris ac edifitiis non usitatis"* 1432(Fig. 2), illustrates the first beam reinforced on the top by one kingpost and two rafters with a reduced height, able to employ the continuous beam only on tensile strenght.

Leon Battista Alberti (Alberti 1989) describes the connection of more elements in order to obtain *arcus vim*, static behaviour of an arch. The *compactae trabis*, jointed so reinforced, works as a cord that constrains opposite strenghts (stress of rafters and strain of chain).

Besides the low truss configuration, constantly suggested by treatises, there are the armate travi by Francesco di Giorgio Martini, o legnio armato by Leonardo da Vinci (Fig. 2), the structures described on our introduction.

The technology of trave armata allows to assemble small, shaped elements jointed by teeth and vertical nails in order to obtain a single beam with great dimensions.

The four pieces beam, drawn by Leonardo has a static behaviour comparable to an arch, due to the insertion of the key and the bending of the tiebeam. The pre-tension impressed to the beam makes more fixed connections because teeth are automatically closed when all the elements are settled.

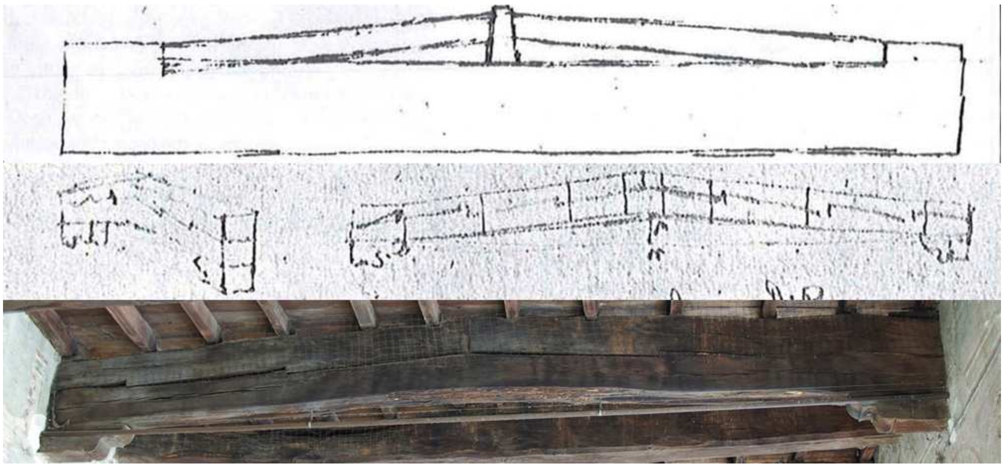

Figure 2: Drawing by Taccola and Leonardo, and beams of the Pandino's Castle (Cremona)

Beginning to XVII century from Galileo's studies, there is more consciousness about ratio of beam's dimensions and about the response of beams to exercise load.

This knowledge appears in manuals and treatise of building art, in which the need to obtain hight sections and to reduce the employ of wood improves the method of composite beam, better way than overlapping single beams.

In 1627 Mathurin Jousse published, in “Le Theatre de l’art de charpentier”, beams reinforced by three different framework. Jousse gives precise dimensions for elements of reinfocements (décharges), lenght of teeth and different iron fixing elements.

He pays a special attention to configuration of wooden elements, binding of beam, cut of teeth. The first Jousse's model is intermediate to beam in three pieces.

The “Manuale di Architettura” by Giovanni Branca (1629) recommend rectangular section for beams with 1/2 or 5/7 width/height ratio. He suggests different solutions to engage horizontally beams to avoid the inflection under the their and exercie's laod, in particular image F shows a scheme in four elements.

Francis Price, in “The British carpenter” 1733 (Fig. 3), explained a manner of trussing girders to cover more than 24 feet. He reccomends to use english oak, with section of 4x3 o 6x4 inches.

Three elements, thin kigpost and rafters, are fixed at side of one beam and their lodging hollowed out on the side of another beam, in the negative. The elements are fixed with iron bolts.

Price's assembling inserts truss scheme into the height of the beam.

In his Traité, J. Ch. Krafft (Krafft 1819) (Fig. 4) says that when the plan of a building needs floors extraordinary wide, wooden beams are too weak to underpin loads, or too short for the span which have to cover, the “art” can fills these lacks.

Krafft knew that rectangular section offers the best resistance to bending and the height is the fundamental parameter. Through the combination of several pieces of wood one could be set up *Iron-belted-beams (poutres armées (F) – Eisen verbundenen Balken (D)*) with considerable height.

The first sample illustrates a beam obtained laying on two elements, joined with teeth and wedge (or keys of pressure), iron bars and nuts. In the second sample the same truss beam saw in Price's Treatise and the in third one a variation of it. Krafft recommends to put a thin sheet of metal between opposite pieces to avoid mutual damages.

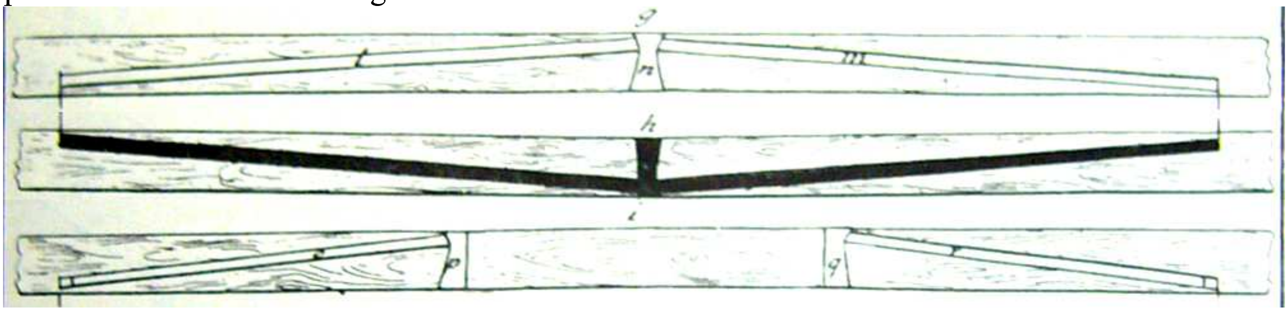

Figure 3: Truss girders by Treatise of Price

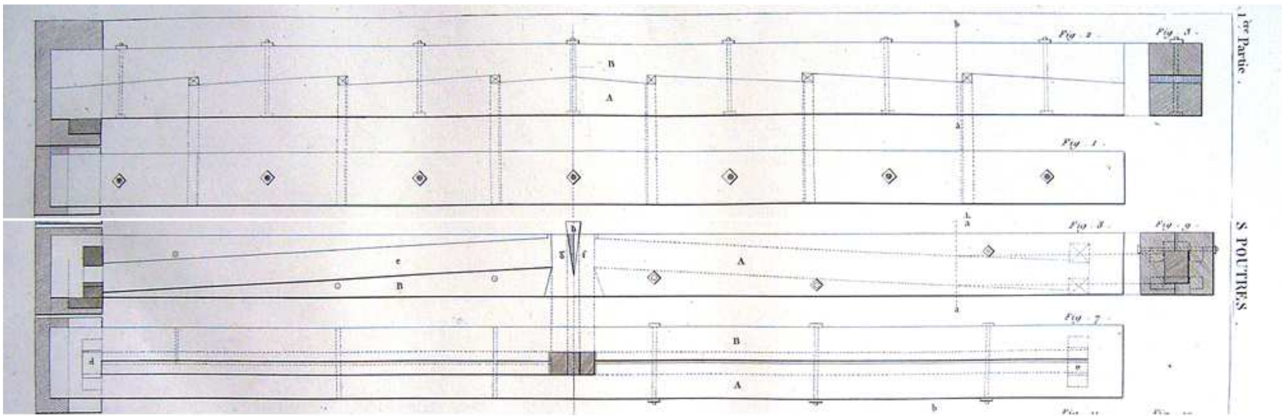

Figure 4: Some different "poutres armées" by Krafft

J. B. Rondelet in *"Traité theorique et pratique de l'art de batir"* (Rondelet 1802-1817) (Fig. 5) reproposes Jousse's composite beams, pointing out the first model as the more resistant and showing others solutions to strengthen beams as bending the upper pieces and cutting the lower one in order to keep the first bended; in this way the beam become one-third more resistant than a single beam with the same size.

In "*Dell'arte pratica del carpentiere*" 1827, F. Pizzagalli and L. Aluisetti divide reinforced beams in simple and composite: first reinforced by joists, boards, iron bends, bolts; second made joining two or more beams by means of "well closed detents, bolts, etc..." to form a single piece. Authors specify that if you joint pieces with iron bolts, setting them working together without lying eachothers and avoiding mutual bending, you will obtain a stronger strength.

The two Italian authors are inspired by Rondelet and Jousse for some simple reinforced beams and by Treatise of Krafft, for considerations about the distributions of stresses in the beams and some composite beams models too.

Timbers employed, mainly larx or oak, must be without nodes, well seasoned, smoothed over surfaces fitting together and cut perfectly on teeth; between joints is recommended to place sheets of lead, and place brackets around the point of main effort.

Lackings even in this case refer to calculation and verification of composite beams.

Gustav A. Breymann (Breymann 1851) defines the composite beam (verzahnte träger) as the most complex and hard work for a carpenter. He shows beams in three pieces and four teeth and in five pieces, two below and three above, in accord to an outline unknown in the antique beams.

Breymann point out teeth like the weak point of composite beams and recommends to insert wedges (verbübelungen) in hard wood or iron, forced in when the beam is already bolted, to avoid sliding.

A metal sheet or a wedge has to be inserted between the rafters' heads to put in tension the upper part of the beam.

Other accurate instructions concern rafters and tie beam scantling, according to the overall section of the beam, similar to those in others publications of the nineteenth century.

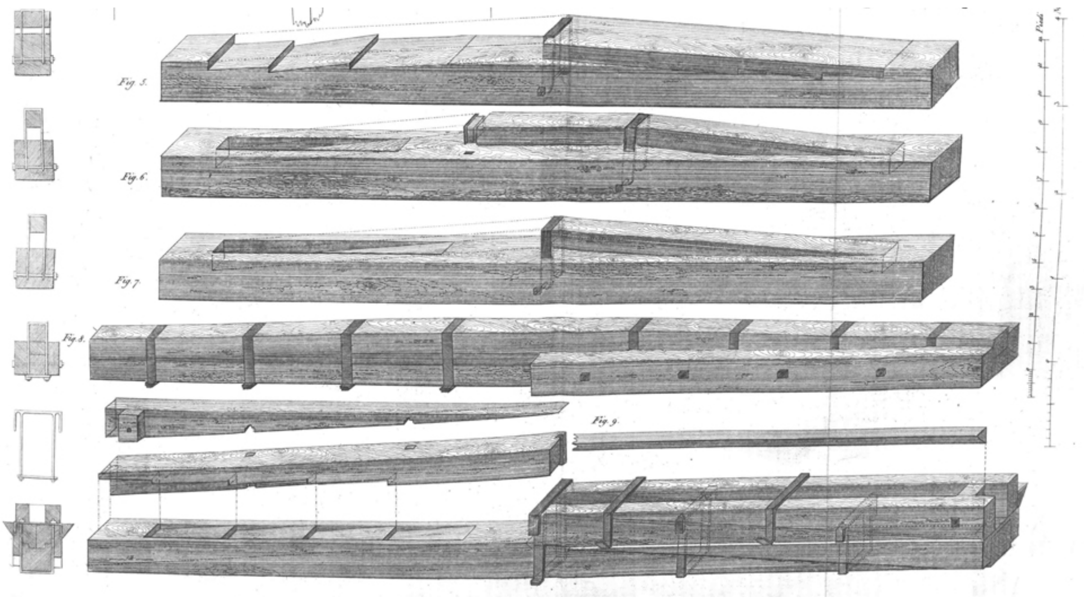

Figure 5: The Jousse's "poutres armées"in the Traité by Rondelet

Modern composite beams, like those by Breymann, require the the tie beam bending obtained by placing a thickness under its central part and pressing the ends to have a rise of 1/60 of the span, which is kept until the end of the assembly. This system looks like the one drawn by Leonardo da Vinci. Tie beam can be bended also by shaping of its bottom side. If the assembly has correctly carried out there will not independent movement of the parts and the beam will work like a single piece of same dimension and shape.

Pubblications so far examinated recognize the improvement of mechanical performance due to composite beams but never suggest methods for their calculation or verification compared to a hypothetical single piece beam of same dimensions.

An attempt in this direction is in "L'architettura del legno" 1883 (Fig. 6), a theoretical and practical manual for designer, which defines travi composte those composed by some pieces joined in order to obtain a cross section able to supports more efforts than commercial beams in one piece. The base principle is that the bending moment of a rectangular section is directly proportional to the square of the height, hence the need to increase the height of the beams.

So the attention moves on joints and their holding out against opposite stress, and on the strenght of wood fibers. In a beam composite of n overlapped pieces (b=width h=height) with working teeth the strenght is equally to a single beam with width b and heigth nh. Infact if the elements are sliding the strenght is 1/6 b n h2, , if are fixed is 1/6 b n2 h2.

The assembling may have only teeth, or teeth with wedges. In the first case beams have odd number of pieces 3, 5 or 7. The advise is again to insert iron stirrup or bolts to close the elements and to insert sheet of metal between opposite surfaces.

Given h=height of the beam, the width of teeth must included among 4/5 and 6/5 *h*, and their height 1/10 *h*. Teeth are traced by this procedure: height AC is divided in 10 equal parts and AB=6 parts, BC=4, Bp=1, ED=4, DF=6, DS=1; draw lines PD and BS divided in equal segments among 4/5 e 6/5h, then draw teeth perpendicular to BS.

Bolts have 2 cm diameter. The bending of the beam is 1/60 until 1/100 l, this is impressed with two hydraulic rams at the ends until bolts are inserted. Again wedges are recommended.

The strenght of a beam realized in this way is ¾ compared with a single beam with same dimensions, so the request height of composite beam is 1,1 or 1,3 times of the heght of a single beam.

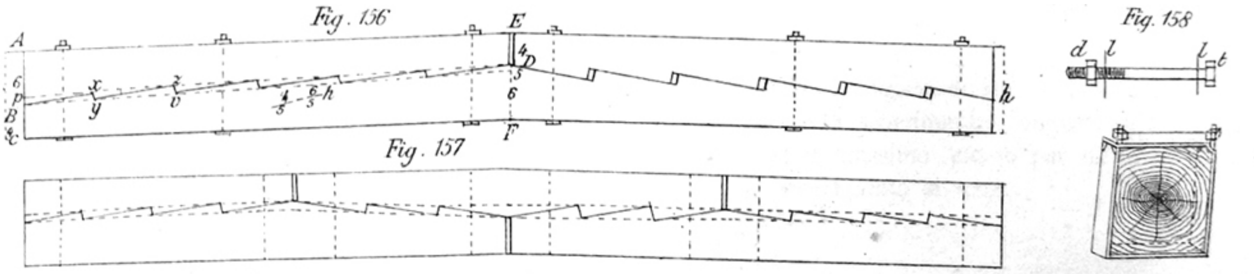

Figure 6: Way to draw and assembly a composite beam in "L'architettura del legno"

Conclusion

The composite beams in modern treatises are an evolution of historical "armate travi", refined and codified at the light of construction's science but treatise contains also more complex configurations very different from the ancient composite beam. The assembling is simplified due the use of wedges to improve teeth, increasing in number of teeth in order to distribute surface tensions and, finally, by the employ of industrial iron bolts instead of nails.

Nevertheless the concept remains the same and the models of the nineteenth century may be assumed to get ready a calculation procedure to verify the ancient composite beams.

A lot of similarities in proportions between ancient structures the characteristic factors we must to consider to elaborate an operative calculation model: geometry of the beam, wooden species, bending of tie beam, possible shoulders, number and dimensions of teeth and position of hand-made nails.At the end of this research we will report first outcomes about determination of the actual behaviour and the strenght of composite beams in order to preserve these singular structures.

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