Wooden composite beams:
A new technique in the Renaissance of Ferrara

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This paper deals with research regarding a singular technique adopted by Renaissance carpentry. The technique consists in the assembly of timbers whose size is shorter than the span to cover (and in some cases the span can be quite considerable).

The resulting composite beam features an arch-like internal mechanical behaviour, which considerably reduce the inflection of the beam.

The following wooden elements (usually three or four) are used to construct the beam:

1. Tie-beam: a single element, located on the intrados, usually curved upwards and mainly subjected to tension;
2. rafters: placed symmetrically at the extrados and subjected to compression;
3. dowel (or key piece): additional central piece whose function varies according to the type of beam.

Two other parts, called «abutments» (4), are designed to give the beam a regular extrados.

The various pieces are connected by notches which allow two contacting components to fit together and prevent them from slipping, and metallic riveting which passes through the entire structure (mainly consisting in nails inserted from the extrados and which feature a riveted point).

In general there are three notches on each side, even if the first (the one nearest the extremity) is hidden because incorporated into the masonry.

This technology is widely distributed throughout Ferrara, and it is not restricted to just the most important
buildings (buildings belonging to the aristocracy, the upper classes and monastic complexes), but it is also found in ordinary buildings. Such widespread distribution is partly due to the good state of conservation of the parts of the city built during the fifteenth and sixteenth-centuries, and is certainly due to historic conditions which determined its large scale use.

The Ferrarese types of composite beam belong to a period which includes the first half of the fifteenth century and the second half of the sixteenth century, during which various techniques were tried and tested resulting in differently shaped composite beams with similar static behaviour.

«Dowelled» beam

This beam essentially consists in two elements: the tie-beam and the dowel. It is achieved by working an entire beam, with the aim of giving the intrados a curved profile. This effect is accomplished by replacing a portion of wood removed from the central part of the extrados with an element called a «dowel», which is longer than the removed wooden profile. The dowel is inserted after the incision made on the extrados has been widened during the curving process. Thanks to this solution, the dowelled beam does not require any notches.

«Three piece» beam

This is the type commonly mentioned in fifteenth-century theorisations and in nineteenth-century manuals.

It consists in three elements which behave like a «truss»: a single tie-beam under tensile stress, featuring notches, and two compressed upper rafters.

In general there is no or a very slight curvature. If present, any abutments are just straightforward finishing touches introduced to regularise the extrados.

«Four piece» beam

This system features four structural elements: the single tie-beam under tensile stress, two compressed upper rafters and a central key piece, which tends to be rectangular.

This type of beam generally features a curved tie-beam intrados.

Given the geometrical configuration of the rafters, the abutments are relatively short as regards length and height.

«Six piece» beam

This is the most mature, widespread and typical in the Ferrarese environment. It consists in the assembly of a (tensile) tie-beam, (compressed) symmetrical rafters and a central key piece. This beam also features a curved intrados and the abutments are higher than the ones found in the other types of beam.

Figure 2

Pattern of the four different type of composite beams with wooden elements indication: 1 tie-beam; 2 rafters; 3 dowel; 4 key piece; 5 abutments

HISTORIC INVESTIGATION: THE LOCAL SITUATION

The city of Ferrara was one of the most fertile centres of Italian Humanism as well as home to the Court of the Este family, advocate of a cultural policy linked to the image and prestige of the State. Through a careful re-reading of cultural conquests, the Court was able to grasp at the chance for renewal at the right moment: a symbiosis between «cenacolo» and «officina» meant that this transition took place in accordance with the plainly visible inheritance of town tradition, which was gradually innovated from both an aesthetic and a strictly technological point of view.
Thus this «Ferrarese tendency» to modernity is a peculiar phenomenon which, having been able to resist the most «forced» attempts at innovation, has acquired a unique relationship with the local context.

As of the second half of the fourteenth century, through the expressions of courtly life linked to the rural environment, this city nestling in the flood plain of the river Po redisCOVERS that rapport with the concept of natural space where it is possible to identify the assumptions for redefining urban space.

Structures taper away until they define a construction installation characterised by strong permeability and, especially on the ground floor, by the capacity to integrate with open spaces, translated into gardens, parks, deep loggias: the privileged sites of the new *modus vivendi*, and «places» where the intellectual *otium*, banquets and games are a necessary complement of the construction installation.

The meaning of this special construction, a manifestation of the relationship between building and earth, generates an image of the «suspended» building, where the lived-in volumes are supported by slender structures, a framework consisting in the columns of loggias and courtyards and by a few masonry walls horizontally connected by the main framework of the floors. In this context, walls and boardings become simple curtain elements, whose material effect is further reduced by the application of extensive pictorial and decorative surfaces.

The result is that the section of the buildings (which rarely exceeded one floor above ground level), has a persistently strong horizontal predominance, thus capturing the much sought-after image of peace and relaxation within the same architectural context.

From the first half of the fifteenth century, important buildings gradually began to appear in the city, the homes of noblemen connected to the Court of Este. It is possible to identify the constant presence of a true «spatial fulcrum» in the architecture, consisting in a loggia which looked onto a park or courtyard and which was topped by the main hall. This distribution system offers an element of mediation between the strong effect of continuity on the ground level and the overhanging construction nuclei. In the pattern of the double open loggia, which fully supports the hall on parallel rows of columns and places the areas facing each side of the loggia in direct spatial contact, this solution reaches its maximum level of expression.

On the basis of this concept it is possible to see the creation of prestigious environments of often exceptional size, which required the utmost construction skill and considerable technical ability by the engineers and the carpenters of the time.

For this reason the use of composite beams became a necessary condition and their presence in fifteenth and sixteenth century buildings in Ferrara does not only characterise a particularly significant architectural event, but determines the Renaissance image of the entire city; composite beams are a symbol of extreme technological experimentation and the maturing of construction practices in Ferrara itself.

The following data related to particularly interesting case studies illustrates these concepts:

— in 1435 construction began on the «Delizia» of Belriguardo in the area around Voghiera, just outside Ferrara; the building was conceived as a place for entertaining, and went on to become the centre of the Duchy during the summer months, able to offer the courtiers, gathered around the figure of the Prince, various opportunities for intellectual amusement and physical recreation. Archive documents quote
the building as being an example of excellent construction expertise, especially for the carpentry used to build the floors of the central building nucleus; here a gigantic hall was built (called the «Sala del Ballone» because it was used for a traditional ball game) located above two grandiose salons measuring 25 m × 15.80 m and about 10 m high. The few and partial testimonies regarding the structure that supported these enormous spaces confirm the presence of composite beams with a transversal section equal to 30 × 90 cm.1

— Palazzo Schifanoia is another example of construction expertise. This building was started at the end of the fourteenth century as a place of entertainment and went on to become one of the most important sites of political power during the coronation of Duke Borso d'Este in the second half of the fifteenth century. The palazzo underwent large scale transformation between 1465 and 1469 when the «Salone dei Mesi» was built, located above an ample loggia which linked the main entrance to the rear garden. This audacious structure consisted in 7 «six piece» composite beams covering a span of about 12 m. Unfortunately only a few traces of this structure remain because serious static problems brought about the gradual closure of the open loggia spaces during the nineteenth century.

— On the other hand, Casa Romei (1440–50) preserves its original spatial concept, in spite of the subsequent building phases which have characterised its construction; it is the only case in Ferrara where the double order of porticoes around the internal courtyard has been maintained. The loggia, Figure 5, on the south side of the courtyard (which supports the main hall), is particularly interesting because the ceiling features three different types of Ferrarese composite beam (three, four and six piece beams).

— The main element in the «Palazzo di Renata di Francia» (1475–91) is the double loggia, Figure 6, attributed to Biagio Rossetti, where the use of composite beams has allowed for the enormous space overhead to be suspended on the straightforward pointed structure of the colonnade.

To complete the historic picture regarding the use of this technology in Ferrara, it is worth mentioning the numerous cases of superelevation carried out on religious buildings: the volumes of the large refectories were often divided up by intermediate floors, or the «ex novo» construction of superelevated floors to create halls and oratories. In these cases, the
replacement of generally trussed ceilings with flat horizontal ceilings featuring composite beams, often caused a «thickening» of the structure which subsequently reduced the interaxis and required additional bays to support the new loads.

ANALYSIS OF THE SOURCES

A more far-reaching research, based on the study of documentation from the fifteenth to the seventeenth centuries and nineteenth century manuals, places the first experiments using composite beams in construction at the first half of the fifteenth century. Nevertheless, the first examples of wooden composite systems expressed on paper date back to the De Architectura by Vitruvius: Roman building techniques included the use of joints shaped like «freccia di Giove» applied to the «Opus Craticium» system and the use of coupled beams which had the task of increasing the strength of structures covering large spans.

The oldest graphic representations of composite structures, created to overcome the problem of finding suitable material to cover exceptionally large spans, belong to the Gothic age and can be found in the drawings by Villard de Honnecourt (first half of the thirteenth century).

The concept of the composite beam finds its first specific reference in the De Re Aedificatoria by Leon Battista Alberti, finished in about the mid fifteenth century; no specific terminology is employed, but there is an attempt to describe the mechanical behaviour of an element made up of multiple parts and designed to cover large spans:

«Sin autem erunt arbores minores, quam ut queas integram unico ex trunco trabem ponerer, plures in unam compacturam coagmentato, ita ut in se arcus vim obtineant, hoc est, ut superior compactae trabis linea fieri nequicquam possit ponderum pressura brevior, et contra inferior linea fieri haud possit longior, sed quasi corda ad superadactos, qui sese contrariis frontibus protrudant, trunco abolitandos nervoso sistat captu.» (Alberti 1485, liber 3, XII)
The passage by Alberti highlights how the static behaviour of a composite beam made up of three appropriately assembled wooden elements provides a «simple truss» effect, where the applied loads are transmitted directly to the constrained extremities, considerably reducing the inflection of the beam.²

The sketches by Mariano di Jacopo from Siena (called «il Taccola»), included in the Liber tertius de ingenibus et edificiis non usitatibus dated 1433, take on special significance in this regard. The sketches include the very first direct reference, even if in a still intuitive form, regarding the possibility of transferring the «truss» function to a ceiling beam, thus considerably reducing the slope of the rafters and the size of the king post.

It is not possible to confirm with any certainty that the beam described by Alberti is a development of this structure of still dubious load-bearing capacity; nevertheless the design of a much lowered truss seems to be the most convenient way of composing a single beam made up of various pieces.

The fifteenth and sixteenth writings by Leonardo da Vinci, included in the Codex Atlanticus, contain numerous notes on the theme of composite beams. It is possible to observe the continuous attempt (repeated in various manuscripts) to find new ways of building a beam made up of various pieces, most of which slotted into each other. The subject of Alberti’s investigation re-appears in a series of experiments regarding the different ways in which a wooden element can be curved; Folios 91 Verso and 139 Recto include four piece beams very similar to those already in use in buildings in Ferrara during the 1430s, Figure 10.

1. Leonardo, Codex Atlanticus, f. 139r.

2. Ibidem, f. 91v.

3. Ibidem, f. 917c-r.

Figure 10

The studies by Leonardo da Vinci tend to research aspects regarding construction techniques, such as the possibility of physically impressing the curvature on the tie-beam, how to cut notches and how to connect the various components.

Leonardo draws tools, which he probably thought up himself, useful for carrying out these tasks; in particular more than once there is a sketch of a trestle, Figure 11, made up of two slanting planks (rafters) and a worm screw, used to transmit the necessary force to the tie-beam and thereby causing it to curve.

He carries out in-depth research regarding the construction processes used to build the composite beam; the drawings are accompanied by comments:

«Piegaloprima, poi ontaglia e fa che desse intagli siano disegnati col fil piombato, e commetti innanzi ch’è scia da la vite.» (Leonardo, f. 946r.)

On the basis of these important contributions, nineteenth century Manuals, and Breymann in particular, offer detailed and exact descriptions of...
construction geometry: how to cut notches and the proportions of each single piece. The layouts given by each author do not widely differ, the only difference is the degree of detail used to reproduce the main dimensional ratios; these were obtained not only by considering the geometry but also on the basis of static computations. The single parts are generally fractions of the span, of the height or thickness of the beam and, in the most detailed drawings, strict relations appear between the different heights of the tie-beam.

The constant reference made to a curvature impressed on the beam during the very first work phases links the descriptions outlined in the manuals to Leonardo's handwritten notes. The curvature was impressed on the piece of wood before the notches were cut, whereas it was only released once the entire connection process had been carried out, thus providing the element with an initial stress state.

**Technological Analysis**

The study of historic building methods and the interpretation of historic construction phases have made it possible to define the evolution of the composite beam. This is confirmed by the possibility of recognising in the geometry of the various types of composite beam, the presence of proportional geometric patterns used to model the pieces to put together.

**Distribution through time of the different types of composite beam**

The distribution of the beam typologies through the whole city, related to different historic periods, highlights, as a first stage, beams belonging to the

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*Leonardo, Codex Atlanticus, f. 91v.*

Figure 11

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*Figure 12*

Plan of Ferrara and chronological table which show the diffusion of composite beams in Ferrara between the 15th and the 16th century
«dowelled type», which theoretically preceded the more mature «four piece» beam.

During the years between the second half of the fifteenth century and the first half of the sixteenth century, the «six piece» beam was mainly used, especially in the most important buildings, where it was necessary to cover large spans or where «serial» use was made of the beam system.

Therefore, starting from the initial experiments, the widespread use of this technique allowed the achievement of a mature phase during the age of Biagio Rossetti, marked by a strong standardisation of the typology and by the development of the special characteristics which allow one to talk of a «Ferrarese beam».

Structural indications present in the documentation

On the basis of studies into Renaissance documentation, two different interpretational «patterns» have been defined as regards the beam-typology and its behaviour.

The first appears in the document by Leon Battista Alberti and reports the «triangular» behaviour of the «three piece» beam, or the triangular layout of the forces.

The same structural pattern appears in the drawing by Taccola, who perceives the possibility of its application to a straight beam based on the plan of a «lowered truss» beam. The migration from the «reinforced» beam solution to a composite beam with a constant section is entrusted to the more extensive use of notches between the contact surfaces.

Leonardo da Vinci draws a composite beam whose main characteristic consists in the curvature of the tie-beam and which coincides with the Ferrarese «four piece» beam.

The different structural interpretation of the two authors regarding the «truss» behaviour and the «arch» behaviour strengthens the theory of a «double genesis» and the parallel development of the composite beam in Ferrara during the same period. The «six piece» beam represents the most complex and refined type of beam, which combines the two approaches described by Alberti and Leonardo. In this complexity it is possible to identify the result of the evolutionary timelines which developed during the fifteenth century.

Construction phases of the composite beam

Research into the historic construction of composite beams based on the documentation allows us to identify the construction methodology used by the Ferrarese Renaissance craftsmen and gives a more profound insight into the woodworking techniques employed.

The production phases used to construct the beam can be summarised into four categories which can be assumed as constants for the types of beam identified:

— Curving: the inflection of the tie-beam.
— Shaping: design and creation of the notches on the tie-beam, rafters and key pieces.
— Assembly: the correct setting up and fitting together of the various parts.
— Riveting: permanent fixing procedure, after which the beam can be said to be complete.

Curving: The reference document is the Codex Atlanticus, wherein Leonardo da Vinci suggests the «trestle» solution for the «curving process».

In this solution the tie-beam is curved to create an internal stress state throughout the composite beam; but this poses practical problems as regards the procedures to be employed, making the formulation of further theories necessary. In particular, the possibility is pondered of permanently deforming the tie beam using heat and steam near the middle, a technique used in the shipbuilding industry of the time.

Different structural behaviours and construction technologies apply to the different curving procedures.

Shaping: According to the indications by Leonardo da Vinci, the tie beam must be shaped when the curving has been completed; in fact this provides very regular surfaces on which to place the other components, thus allowing the pieces to fit together perfectly without the need to insert other elements.

But it is possible to speculate that the shaping process of the tie beam takes place in two distinct phases: one before the curving procedure to create the housing for the central key piece, and a second phase, when the notches are cut into the curved wood.

The assembly of the curved tie beam and the upper pieces (the undeformed rafters and key piece), poses
geometric problems as to the possibility of juxtaposing the parts correctly.

In spite of the scant indications, the stages described by Leonardo da Vinci and later nineteenth century elaborations, it has not been possible to accurately reconstruct the most commonly adopted procedures used during the Renaissance to solve these problems.

Assembly: During this phase it is possible to hypothesise the use of a stratagem as indicated in the nineteenth century by Breymann:

«The two upper pieces are placed on top of the lower piece, while the lower piece is maintained curved, the lower piece is then curved even more, not only so as to insert the upper pieces more easily but also to give more strength to the shaped joints.»

(Breymann 1884, 2: 16–20)

The author refers to a further slight curving of the already curved tie-beam which has the aim of enlarging the housings thus making assembly of the upper pieces easier.

The subsequent removal of the additional load allows for an improved and more efficient contact between the pieces, as well as creating an internal state of stress, resulting from the contrasting action exercised by the upper elements.

The cause providing the inflection to the tie-beam is then removed and it is only during this phase of the process that it is possible to contemplate the application of the so-called «abutments» necessary to create a perfectly horizontal extrados.

Riveting: This operation foresees the use of large nails (approximate section of the head: 2 × 2 cm) inserted to connect the structural parts: this guarantees the absence of any differential displacement between the parts. The nails were driven downwards until the point of the nail completely emerged. The point was then riveted at the intrados.

After this the abutments (fixed only by riveting) were applied using smaller nails which only passed through the rafters.

The number of normally observed rivets is one for each notch, mainly located in the middle of two successive notches.

In general the nails are aligned along the geometric axis of the entire beam, unlike present-day mixed wood-steel structures.

Proportional patterns

Over the centuries, the quest for a reliable «rule» which could be repetitively applied to structural sizing has called for the coding of proportions. Experimentation has suggested the necessary variations or refinements needed to obtain results of the desired quality. The parts making up composite beams have also been sized according to the laws of geometrical proportion, applicable to each case thanks to straightforward changes of scale.

This coding has left traces in recognisable evolutionary timelines, where partial modifications to geometrical patterns do not only reveal the development of the technology itself, but also indicate which aspects of static behaviour of the beams the insigneri (engineers) and marangoni (carpenters) focused their attention on.

The span in particular is divided by way of a modulus equal to one third of the span; central key pieces correspond to this modulus as well as the rafters in «four piece» beams.

A similar rule is applied to the shaping of the rafters, whereby the internal notches are distanced according to moduli equal to 1/9 of the total span. This rule is maintained in the first formulas for the «six piece» beam, while in the «three piece» beam, for obvious geometric differences, the division into thirds gives a modulus equal to the value of 1/6 of the total span.

The initial assumption of constant moduli is followed, on the basis of experiments carried out mainly on the «six piece» beam (the results of which were soon applied to the other beams), by the scanning of the notches using a «progressive step»; as regards the geometry described, the notches were moved back towards the supports by a further modulus equal to 1/3 (1/27 of the total span) resulting in the geometry indicated in the Figure 13.

This solution highlights the desire to improve the transmission of the internal forces between the rafters and the tie-beam in areas nearer the supports, thus reducing the flexional effects on the beam.

The comparison between division «by thirds» of the main geometries and the scanning «by quarters», adopted at a certain point in drawings of the key pieces in «six piece» beams, highlights the influence exercised on this construction technique by the units of measurement in use at the time. The main unit of measurement, the «Piede» (Foot), was divided into quarters; each quarter
was called a «Palmo» (Span). Each span was divided into thirds, called an «Oncia» (Ounce).

Therefore, thanks to these historic measurement units and their specific values in Ferrara, it has been possible to reinterpret the type of sizing scales employed, and verify their use with utmost precision in fifteenth century buildings.5

CONCLUSIONS

This research has allowed information to be collected and compared (in part new and in part already known), relative to a special building technique using wooden composite beams, proof of the high degree of technological refinement achieved in fifteenth century Ferrara.

In particular, production and assembly techniques applied to the wooden elements have been re-discovered as well as structural behaviours and rules of proportion between components, memory of which had been lost in time. This investigation has been carried out on the basis of interdisciplinary contents which, when compared with each other, have offered utterly new results.

NOTES

1. The theories regarding the geometry of the beams and the number of parts are based on research into other building sites in Ferrara and examples from Renaissance documentation; there are also obvious analogies with the floor of the «Sala dei Gigli», built in 1472 in Palazzo Vecchio, Florence, whose structure is made of composite beams with a section equal to 105 x 30 cm covering a 15.85 m span.

2. A drawing on the margin of a page in the manuscripts by Francesco di Giorgio Martini (end of the fifteenth century), reproduces the «truss» system described beforehand by Alberti, enriched by the notches shaping.

3. In 1438 Alberti establishes relations with Ferrara and it is very probable that his presence at court also included consultations. The treatise (dedicated to Lionello d'Este and probably ended in 1452), did not start before 1443, the year in which Alberti left Ferrara and returned to Rome. As far as the authors know it does not seem possible, given the lack of reliable sources, to establish where and when Alberti was able to see the «truss» system, or whether it was his own original contribution to architectural practices; it is only possible to observe that in Ferrara the first cases of the «three piece» beam date back to the 1440s–1450s (the portico of Casa Romei). As concerns Leonardo, he may have passed through Ferrara after the fall of the Sforza in 1499, on his return from Milan to Florence, when it has been proved that he made intermediate stops in Mantua and Venice and thereby may also have stopped off in Padua, Ferrara and Bologna.

4. The architectural example of Casa Romei includes three different types of beam belonging to the same historic period. This demonstrates the presence of the distinct types of beam in their primitive form from the first half of the fifteenth century. The typological transformation process can therefore be seen within each single type of beam.

5. For an example, a 96 spans beam pattern, corresponsing to 9.67 meters, could be divided in three parts, 32 spans long; each of these could be simply subdivided in three part of 32 ounces, thus obtaining the initial «constant step» scanning of the notches.

REFERENCE LIST


