

Assessment of Deformability and Collapse Load of Timber Structures Built According to Treatises of the First Half of Nineteenth Century: the Case of the Truss Structures on the Roof of the Town Hall in Ravenna

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Conservation work is not only the action taken to prevent the building decay but, also, expresses the necessity to transmit to the future the ancient construction systems, which can be considered one of the main cultural heritage.

Conservation work is multi-disciplinary and involves many skills which contribute to a reasonable project, which has the aim at recognising the importance and the vulnerability of timber structures.

As the Charter adopted in 1999 states, the most important intent of conservation is to preserve the authenticity and integrity of the historical, structural or decorative, elements. [25]

This necessity requires a very deep knowledge to guarantee, in case of interventions on structures, their conservation and their load bearing capacity.

For all these structures, it is necessary to investigate each element, and the weakness and the strength inherent each the structural design.

The modern methodology should be: the study of the different phases of construction of complex buildings; the check up of the decay of the material and its causes; the analyses of the deterioration of the structural system and its agents.

The instruments for the investigations are: the historical research, the study of the project of each phase of construction, the geometrical survey, the direct inspection with specific methodologies and instruments promoted. [31,32,33]

Aim of the present work is to compare the calculation of timber structures according to a modern methodology and the empirical models adopted in the Nineteenth Century, during the building of the main Italian cities, when the schools for architects and engineers developed and their role became fundamental in designing the building structures.

Moreover, it is necessary to say that in Italy it is difficult to find the documents related the project of structures built in the Nineteenth Century. Many documents, as the specifications, give information only on the dimensions of the structures and their construction, but not on the design. For instance, in the case of "Alighieri" Theatre, designed by Giovan Battista e Tommaso Meduna, the same architects of "La Fenice" Theatre, in Venice, the draft of specifications give some information about the measures of the trusses (which were replaced after the half of the Twentieth Century), but not about the criteria adopted for their design. [1]

Due to this difficulty, in general, a study of the cultural environment into which technicians became qualified in architecture or engineering, is required for a better understanding of the project, also from a structural, and not only for the architectural or stylistic point of view.

Actually the Italian code on structural analyses of ancient buildings requires a deep study of the original criteria adopted for the structural design.

In fact, the knowledge of the constructive systems' criteria is a necessary condition to

establish the “level of knowledge” (“livello di conoscenza” as stated by the OPCM 20/03/2003. nr. 3274, updated by OPCM 03/05/2005, nr. 3431) with which it is possible to determine the safety coefficient to be adopted in verifying the ancient structures under seismic loads. The definition of the “level of knowledge” depends on some parameters, like the following: geometric survey of structures; reconstruction of historical events which affected the structure; the original structural design and its changes; the diagnosis of decay of the materials and the structure; good knowledge of the adopted constructive systems. [23]

The detailed and comparative study of classical empirical models, adopted for the design of timber structures in the first half of Nineteenth Century, can provide fundamental information for the actual interpretation of the behaviour of structures to be repaired and/or structures whose carrying capacity has to be quantified.

The case in study is represented by the timber trusses of the Town Hall of Ravenna. The palace was rebuilt in the Seventeenth-Eighteenth Century and the roof was restored in the first half of the Nineteenth Century. Specifically, one pitch was raised and this fact changed the load distribution on each truss.

In brief, in the 1361 along the *flumen Padenna*, in the same place of the present palace, there was a Bernardini da Polenta's house, used as Town Hall and offices (services' centre). The palace became the centre of the Venetian Government (1441-1509). Under the Papal Government (from 1509) it was used like Law Court. The building, rose across the Flumen Padenna, had two flats in the side in front of Piazza Popolo (the main square) and was composed by modest little houses in front of Piazza dell'Aquila. During the Venetian Government, it was often consolidated and restored: from the half of the XVI Century to the half of the XVIII Century were added several rooms and a new Town Council room in the 1761 Dionigio Monaldini designed the increasing of the Palace, building a best residence, for the Authority, new offices and a new Town Council room in the 1831 the engineer Ludovico Nabruzzi designed the new saddle roof correcting the mistakes of the primitive one, and the sculptor Cristoforo Michelieni restored or rebuilt the stone balcony; in the 1857 Albino Riccardi, from Rome, designed new windows on the three façades and added the Ghibelline battlement for hiding the roof. The design was performed on the occasion of the coming in Ravenna of Pope Pio IX. [26,27]

After that only ordinary maintenance was made. At the half of the 1960, the shape of the roof was changed: one pitch was raised and was supported by a vertical strut resting on one of the principal rafters of each truss.

The trusses were designed in the first half of the Nineteenth Century by Ludovico Nabruzzi (1766-1849) [2, 19] an architect, aspirant engineer, whose culture is based on the humanistic and scientific knowledge transmitted from the teaching of the “ravennate” architect Camillo Morigia (1743-1795). In the library of Morigia [12], now conserved at the “Biblioteca Classense” in Ravenna, it is possible to find some treatises on structural system and architectural construction. In particular there are the books written by B. Forest de Belidor (but also studies by Muschenbroeck, Duhamel, J. Bernoulli) and the treatise by Francesco Milizia. [4, 5, 14, 22, 21]

Between the end of the Eighteenth Century and the first half of the Nineteenth Century, the scientific curiosity on mechanical behaviour, as Timoshenko says [29], was interested in the questions of elasticity and of strength of structures. During the Eighteenth century, the scientific results were introduced in various fields of engineering. The de Belidor's book “La science des ingenieurs” was published for the first time in 1729, but the last edition, with notes added by Navier, appeared in 1830.

The theory explained in this book does not go beyond the results described by Galileo [18] and Mariotte [20], but de Belidor applies it to his experiments to give the rules for determining the safe dimensions of wooden beams, recommending a more rational method for the structural analyses, thinking that the then established practice of sizing the beams was not satisfactory.

De Belidor uses Galileo's results, namely the strength (i.e. load bearing capacity) of a prismatic beam is proportional to the breadth and to the square of the depth of the cross section, and to the inverse of the beam length. Besides, de Belidor states that not only simple beams, but also complicated systems of beams, like trusses, can be analysed and

it is possible to find a method for selecting safe dimensions. [29, p. 42].

In the same time Milizia [21], an architect in Rome follower of the neoclassic culture theorised by Winckelmann, in his treatise "Principj di architettura civile", criticizes the Galileo's statements.

Milizia, referring to de Buffon [8], in the third book writes that the strength of wood is in deep relationship with its weight. In fact, the experience carried out in the second half of the Eighteenth Century by de Buffon, A. Parent [24], P. van Musschenbroek, H. L. Duhamel [6, 7, 29, 13] show that some characteristics of the wood, like working, seasoning, and the loading time before the beam cracking, can deeply influence its strength [21, p. 200, III].

Milizia says that the ultimate strength of a beam is not the one that instantaneously breaks the beam, namely that adopted by de Belidor and other physicians, but that producing an excessive deformation of the wooden beam in a long time. Then, the half of the breaking value has to be adopted to design. This consideration leads Milizia to assume Galileo's rule as to be not always true. [6, 7, 29]

In fact, not all the beams break immediately under load: after a period of time, beams show a reduced load-bearing capacity.

In addition, Milizia [21, p. 168, III] states that a truss can be analysed as a trestle composed by bars connected all together, where the principal rafters act on the tie beam instead of acting on the wall. The struts (and, generally speaking, all the inclined beams) do not need the same square cross section as the horizontal ones (under the same span), because they are loaded by the roof (whose weight is lower than the floor's one) and their slope "increases their strength". Moreover, it is necessary to choose for all the bars the same kind of wood, and the best one for trusses is larch wood.

Despite the statements given by de Belidor and Milizia on the design of trusses (and of inclined beams), at that time no one proposed a method for their structural design.

J.-B. Rondelet, a contemporary of Milizia, suggests, in his treatise "*Traite theorique et pratique de l'art de batir*" [28], a qualitative analogy between the truss elements and the structural components of the floor, but without indicating a clear computational methodology.

Moreover, he underlines that the structural asymmetry and the progressive decay of material affect the truss bearing capacity. [28, p. 119, pp. 62-63, III]. Similar considerations, although some decades later, are given by Cavalieri San Bertolo. [10]

Some additional practical indications, with respect to Rondelet treatise, are discussed on the choice of the truss typology depending on the span.

The truss design was based on experience and empirical rules because the structural behaviour was not clearly understood from a scientific point of view. [35]

In fact, starting from Galileo, and then Euler [15], quantitative predictions on load bearing capacity of horizontal beams have been discussed in many other treatises on building construction (like, for instance, those written by Rondelet, Milizia, Cavalieri San Bertolo, much more diffused in the States of Italy until 1840, about) and their predictions were satisfactory to design purposes.

On the contrary, the design of inclined beams was based on heuristic arguments: Rondelet proposes, correctly, to adopt the horizontal projection of the beam length in his formulas, derived for the horizontal beams; however, he wrongly interprets the obtained dimension of cross section depth as the vertical one, and reduces such dimension to its projection on the direction orthogonal to the beam axis.

Only in the second half of the Nineteenth Century, scientists applied correctly the trigonometric decomposition of forces, and proposed to consider the trusses as made up of members working in tension or in compression. [3,6,7,29,35]

The survey, described above, has been made by the architects of the Comune di Ravenna and some measures of the calculated truss have been verified by the author. From the documentation offered by the architect, the hall covered by the trusses is 10,50 m in width and 33,30 in length. There are 20 trusses and, excepted the last two, whose members' dimensions are different, they have been built with the same dimensions, technologies and wood.

The results of visual analyses show that the wood is, probably, Italian larch, and it seems

to be in good conditions of conservation. The vertical struts, that are supporting one of the pitches, are made in Italian poplar: their conditions of conservation is not good, and, to all the appearances, the struts seem to be attached by insects and, at the moment, it is difficult to say something else. [11, 30]

Except for few cases, only the king post have an iron strap that connects itself with the tie beam, while the other joints, generally, are not reinforced by iron straps.

Only one pitch was raised and this fact changed the load distribution on the trusses: in fact, the raised pitch is supported by a vertical strut that leans on one of principals rafter. It seems reasonable, that this occurrence produced the disconnections of some members, like principal rafter and strut or strut and king post.

Some numerical analyses have been performed, with the aim to validate the above description of joint failures and to assess the reduction of the load bearing capacity of a truss after the pitch raising.

At the moment, it is unknown if the insertion of the vertical strut was verified from a structural point of view.

The span covered by trusses is 10,50 m. The high of truss is 267 cm. The distances between the centres of trusses are not regular: from a minimum of 140 cm about to a maximum of 240 cm about; the calculated load on the roof is 280 daN/m². Each truss element has the dimensions reproduced in the following table:

Geometrical sizes	breadth of cross section (cm)	depth of cross section (cm)	length (cm)
principal rafters	20.5	26.0	604.3
tie beam	21.0	25.5	1132.0
king post	20.0	20.5	238.8
struts	20.0	15.5	194.3

Milizia does not establish the dimensions of the elements and Rondelet, generally, refers about examples becoming from ancient or existing buildings and French treatises on timbers structures.

The data are compared with the sizes proposed by different, more recent, treatises, as those written by Luigi Cattaneo and Carlo Formenti [9, 16]. It can be observed that for comparable cross section dimensions and span, the maximum estimated load (per unit length) is higher then that actual one.

	principal rafters (cm)	tie beam (cm)	king post (cm)	struts (cm)	span (cm)	maximum distance between the centre of trusses (cm)	load daN/m
Cattaneo	22x28	28x36	30x30	20x20	1200	400/450	675
Cattaneo	18x24	25x30	25x25	18x18	900	400/450	675
Formenti	28x22	28x22	22x22	-	800	450/500	720

An assessment of the bearing capacity of the truss can be done according to the UNI EN 1995 Eurocode 5 Design of timber structures. [34]

The geometry of the truss shows a slight asymmetry; the structure has been discretised by classical beam finite elements, enriched with the shear deformation model. The tie beam has been assumed as clamped at the ends, while the principal rafters are considered as hinged to the tie beam. This last assumption follows from the fact that the principal rafter rests simply on the tie beam, without any iron straps.

The applied loads consist of the self weight and of the concentrated forces (due to purlins) acting at the extrados of each principal rafter.

In absence of experimental data, the material parameters are assumed from the literature:

Larch (<i>Larix europea</i>)	
Density (at 12% moisture content)	650 daN/m ³
Modulus of elasticity ($E_{0,mean}$)	120000 daN/cm ²
Ultimate compressive stress parallel to grain ($f_{c,0,k}$)	300 daN/cm ²
Ultimate tensile stress parallel to grain ($f_{t,0,k}$)	200 daN/cm ²

[17, pp. 378-406]

The following conditions are assumed in order to carry out the structural analysis:

- the meeting points of the axes of strut and king post do not coincide, but the difference is very small (less than 1,0 cm), so they are assumed as coincident;
- there are not iron straps between truss members;
- despite the absence of iron straps, between the struts and the principal rafters and between the struts and the king post no relative rotations are permitted, because only compressive stresses arise;
- hinges are introduced in the model between principal rafters and tie beam, because of the absence of iron straps and the tension stresses which would arise if relative rotation would be constrained.

According to [34], the category to which the truss belong in the nr. 2. 60-80% RH, and air temperature: 0-20 °C

The reduction coefficient affecting the ultimate stress is $K_{mod}=0,8$



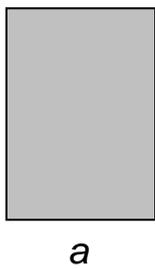
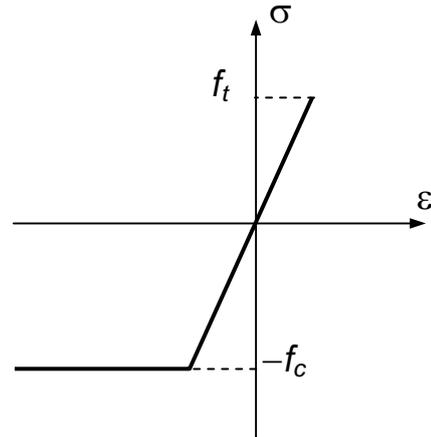
Figure 1. Town Hall in Ravenna: façade on Piazza del Popolo (N. Lombardini, 2007)

Then, ultimate stresses are:

$$f_t = 200 \text{ daN/cm}^2$$

$$f_c = 300 \text{ daN/cm}^2$$

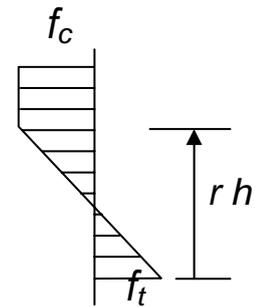
It is assumed, as commonly done [17], that wood grains break in tension at f_t , instead, a sort of irreversible deformation is developed in compression



cross section of a generic member of the truss

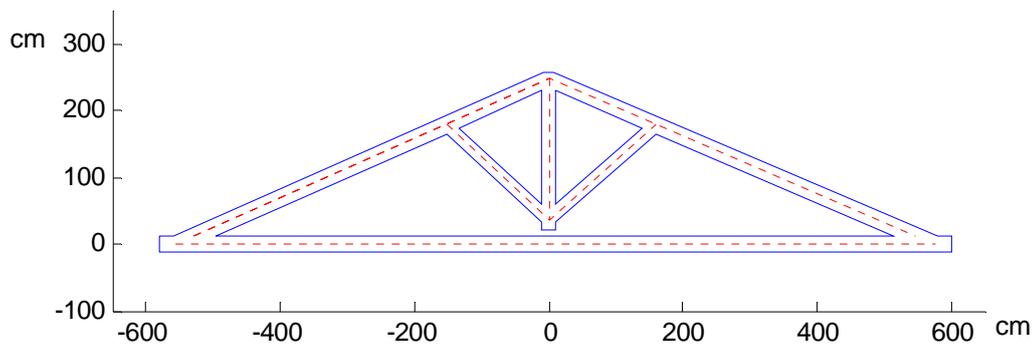


frontal view of a generic member of the truss



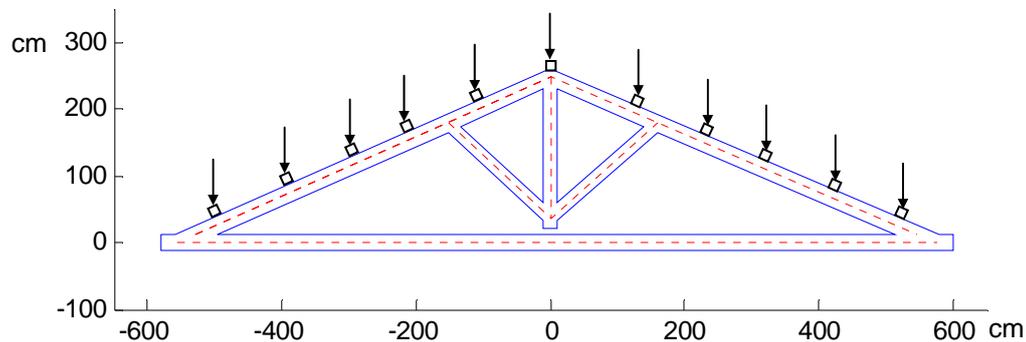
stress distribution at the ultimate limit state of a cross section

Applied loads on the roof: $(120 + 160) \text{ daN/m}^2$

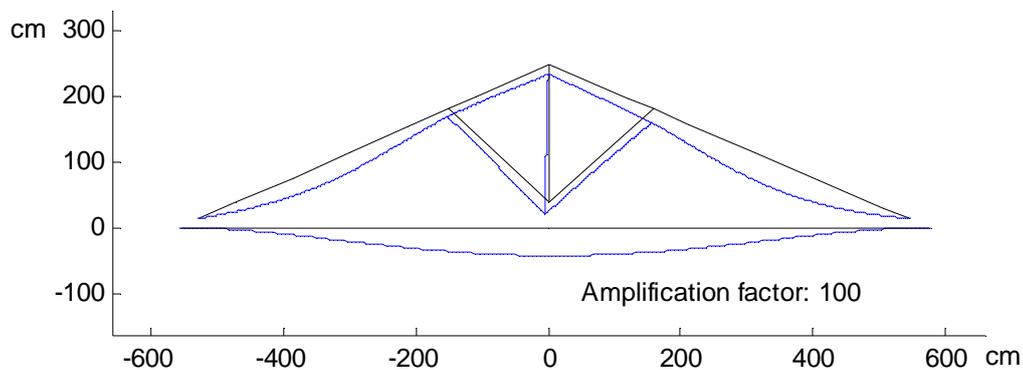


Truss geometry and beam axes

1) Load distributed on the two pitches:

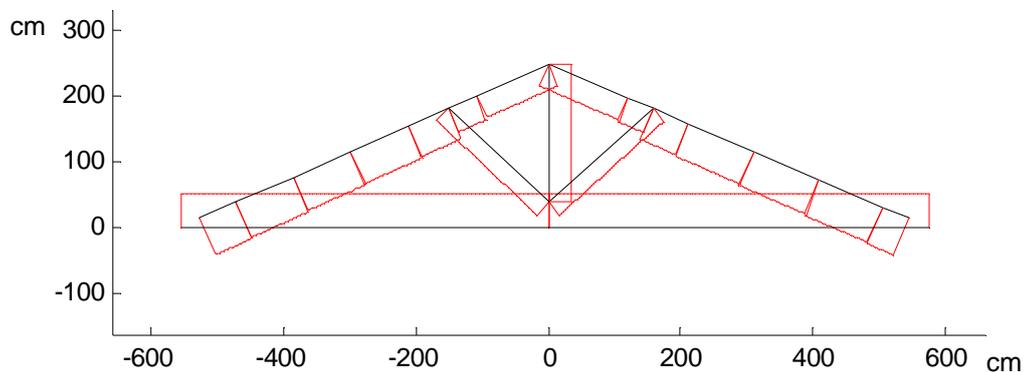


Undeformed and deformed configurations

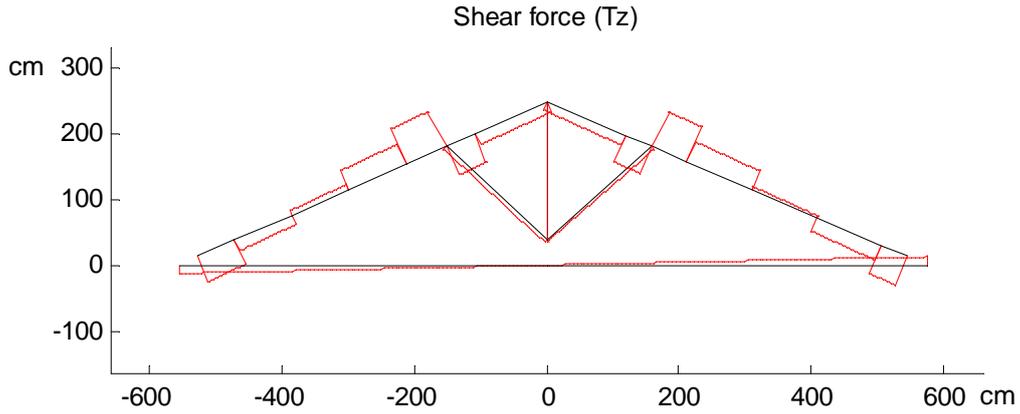


Maximum vertical displacement: 0,43 cm

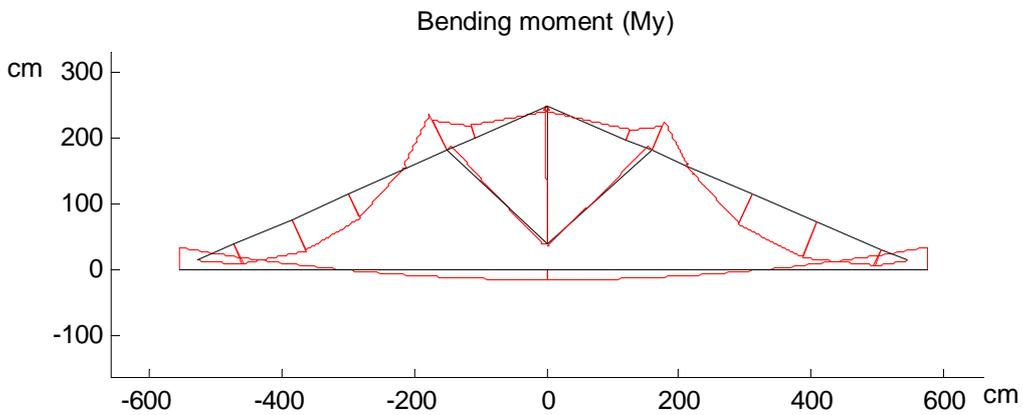
Axial force (Nx)



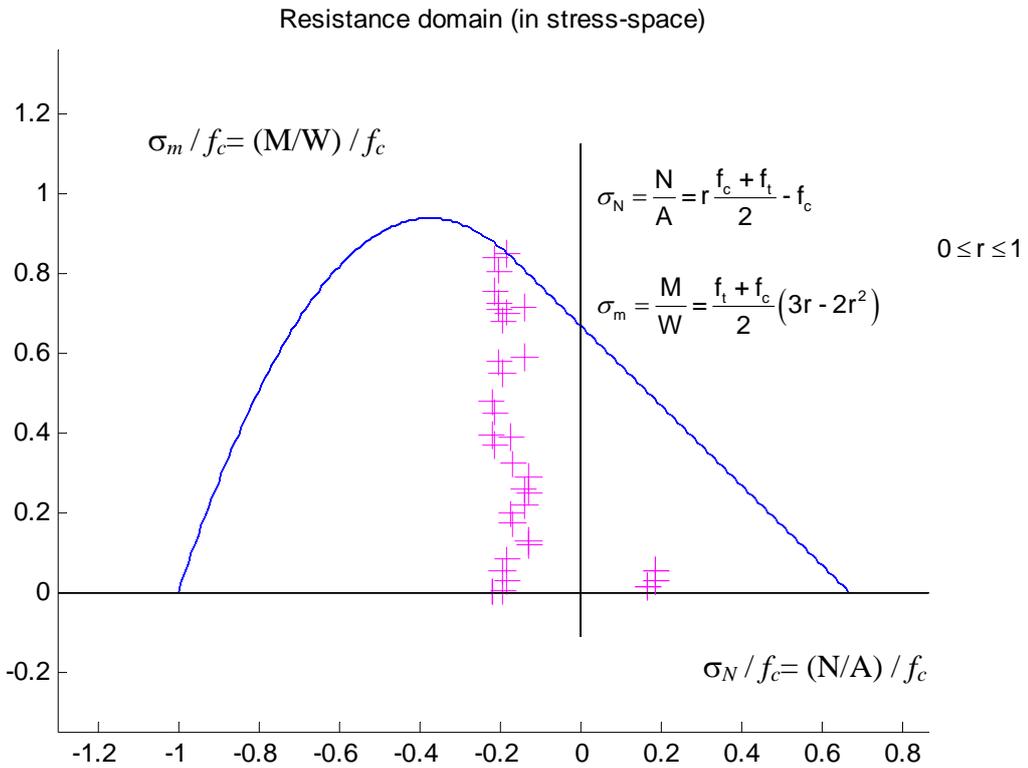
Maximum axial force N_x : 43,1 kN



Maximum shear force Tz: 9,38 kN

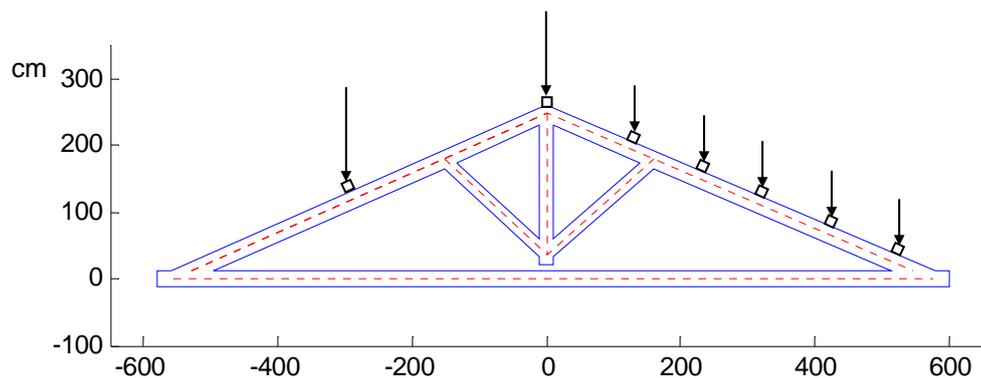


Maximum bending moment My: 678 kN cm

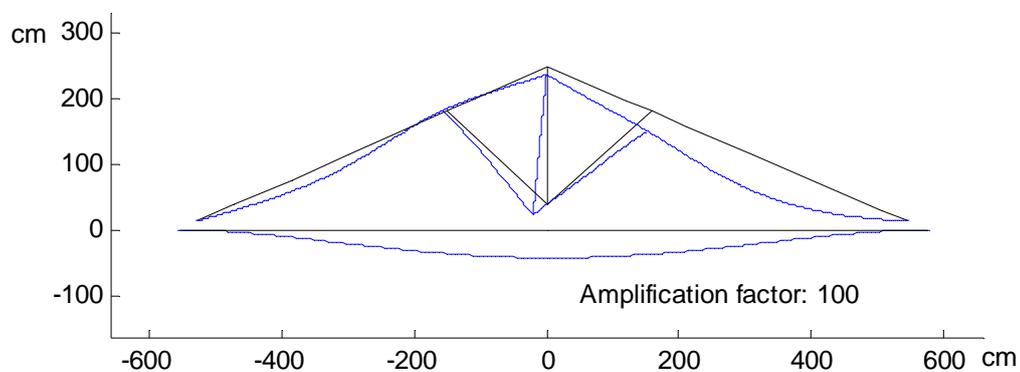


Crosses represent nominal stresses in various cross sections for a load amplification factor = 9,3

2) Concentrated load on one pitch:

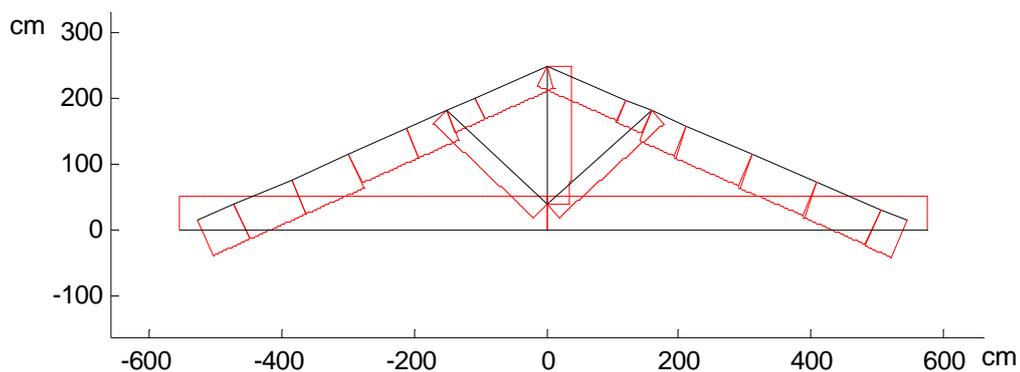


Undeformed and deformed configurations

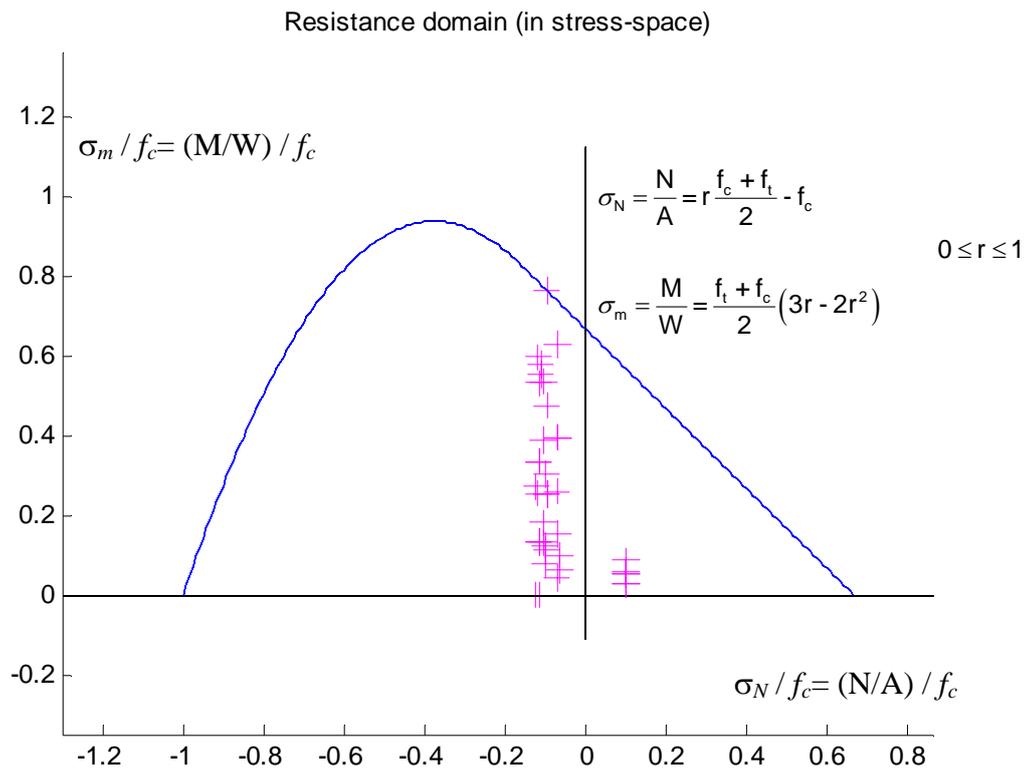
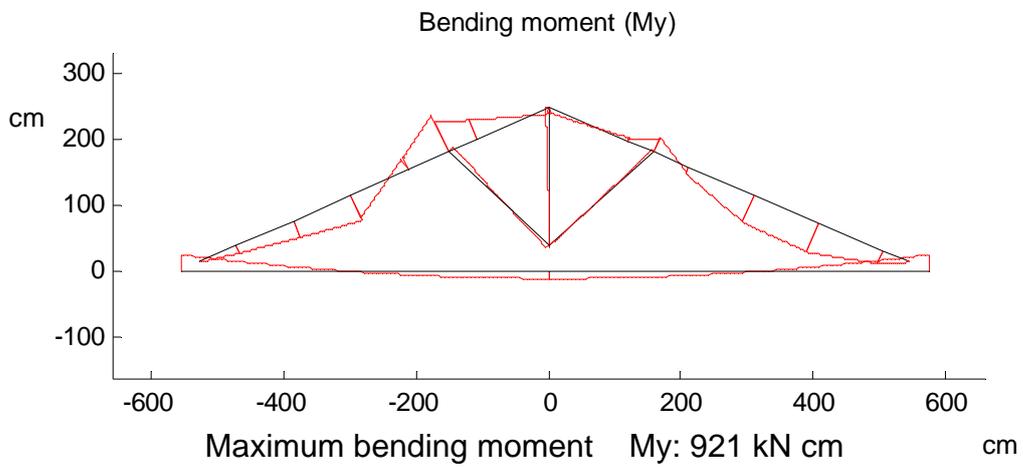
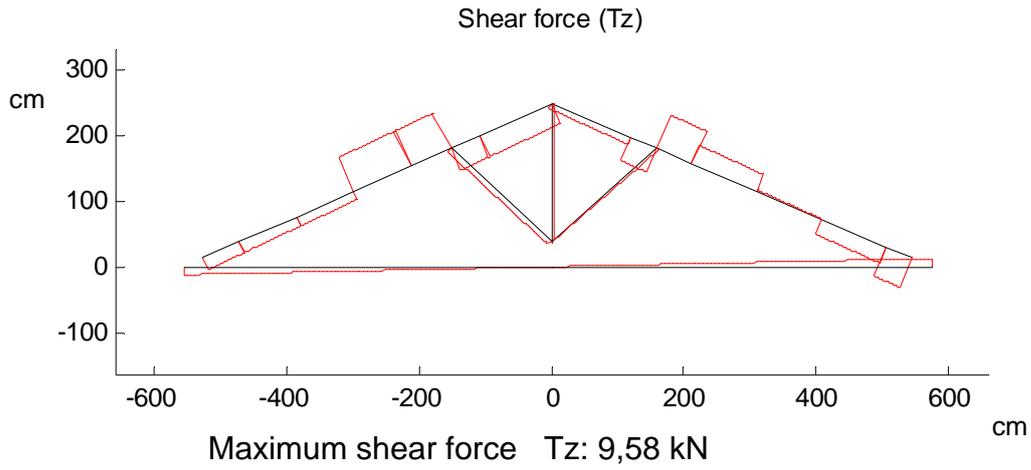


Maximum vertical displacement: 0,48 cm

Axial force (Nx)



Maximum axial force Nx: 37,2 kN



Conclusions

A numerical study of ancient buildings needs both a deep knowledge of structures and the study of the background of the science of construction to guarantee a better understanding of the actual conditions of the structural elements and, at the same time, for choosing the right criteria of restoration and consolidation.

In the present case, the oversize of the trusses and the small distances between their centres (by assuming a good state of conservation of the wood), due to the different conception of the structural behaviour, guarantee a good performance of the trusses.

In fact, the trusses were designed with a quite high safety factor, according to empirical roles adopted in the past.

Probably, the rise of one of the pitch and the consequent asymmetric load distribution, whose consequences on truss structural behaviour was not verified at the time of its construction, are the principal causes of the twists and of the following disjunctions, with consequent rotation of the central part of the truss.

Specifically, analyses performed with a finite element method, with beam elements accounting for axial, shear and bending deformations show that the pitch rising has produced a reduction of the safety factor, with respect to collapse, from about 9.3 to 6.0



Figure 2. The trusses (N. Lombardini, 2007)

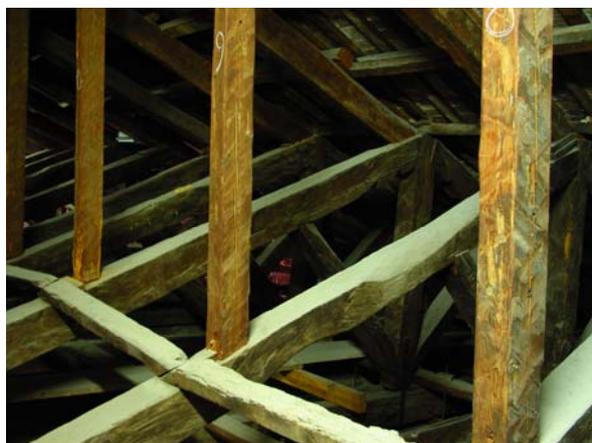


Figure 2bis. The vertical struts (N. Lombardini, 2007)



Figure 3. Joints details. Conjunction between the knee rafters and the king post. (N. Lombardini,



Figure 4. Joints details. Conjunction between the knee rafters and the tie beam. (N. Lombardini, 2007)



Figure 5. Examples of disjunctions between struts and king post at several trusses (N. Lombardini, 2007)



Figures 6,7. Examples of disjunctions between the struts and the knee rafter at several trusses (N. Lombardini, 2007)

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