International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 12 (2018) pp. 10215-10219
© Research India Publications. http://www.ripublication.com

Finite Element Modeling and Analysis of Aged Timber Trusses located in Northern Italy

Claudio Carino and Fabio Carli

Department of Civil Engineering and Architecture
University of Pavia - Via Ferrata, 3 - 27100 Pavia, Italy.

Abstract

A spruce timber truss located in Northern Italy is examined in this paper by finite element analysis, with two possible types of discretization: the first one taking into account the system as entirely composed of 2-node linear elements that coincide with their axis; a second scheme providing, for the tie beam only, a discretization based on 8-node solid elements. This allows, besides validating mutual results, to evaluate, in future studies, the adequacy of any reinforcements employable for the tie beam. In fact, despite the maximum stress for the truss examined yields acceptable values, any possible degradation condition - to be suitably assessed - might alter the mechanical properties of the wood over time.

Keywords: Timber truss, Aged buildings, Finite element analysis

INTRODUCTION

Although the monumental architecture in Italy during the Romanesque and Gothic periods preferred the vaulted roofs, in medieval age timber trusses spread throughout the country for both large monumental churches and smaller buildings, giving rise to many variations. In those structures, the upper components were adapted to the shape of the roof, while the profile of the lower element was determined by the requirements of free height, the shape of the ceiling and the height requirements of the building. Spruce, pine, larch and chestnut represented for centuries the tree species that were mostly used for structural purposes.

Various treatise writers tried to analyze the truss in some detail during the Renaissance period, but in general these studies reveal that the knowledge of the "reticular" nature of the truss had not yet matured. Andrea Palladio was one of the first architects to design the truss with king post and struts, well connected to the tie beam in a rational structure, although not yet fully understood. In the 18th and especially in the 19th century, the truss was studied on a theoretical level, attaining a full understanding of the static functioning, whose principles gave rise to much more complex structures.

The use of timber trusses was maintained in Italy until the first half of the 20th century, sometimes employing metal materials - much more resistant to tensile stress - for the construction of the tie beam, while retaining traditional wooden materials for the other elements. In the meantime, the wooden truss was codified in various handbook texts for the purposes of static calculation, without, however, succeeding, at least until the second half of the century, in reducing its intricacy.

In the light of a finite element (FE) code, this paper focuses on the study of aged timber trusses mainly built in Northern Italy up to the first half of the 20th century. Structural systems with a wide span length and an ample interaxle spacing are taken into account with the aim of computing internal forces and stress values within each individual member. Particular attention is devoted to the discretization and analysis of the tie beam, a crucial element for the correct functioning of the entire structure.

THE TRUSS TYPOLOGY EXAMINED

The typical timber truss examined in this work is a vertical system placed as a basic structure of a sloping pitched roof. It is able to eliminate almost completely the horizontal thrusts, thanks to its internally rigid design, in which the horizontal element (tie beam) nullifies the thrust of the main inclined members (principal rafters).

In particular, the exemplary wooden truss located in ancient buildings of Northern Italy (Figure 1) consists of: two principal rafters, inclined beams that determine the slope of the roof; the tie beam, which forms the base of the rigid triangle and supports tensile stresses, thus avoiding transmission of horizontal forces to the masonry; the king post, a vertical member that connects all the elements, with the exception of the tie beam; two struts, i.e. elements with an inclination opposite to the obliqueness of the rafters, that transfer their compression force to the king post, hence reducing the bending effects on the rafters. A bracket is sometimes present between the king post and the tie beam, with the sole purpose of ensuring the coplanarity of the structure.

In such a structural system the tie beam, with its significant self weight, is subject to both bending and tensile axial force, the principal rafters are bent and compressed, while the king post is weakly subject to tensile stresses and the struts are slightly compressed.

Other orders of elements, alternatively perpendicular and parallel to the truss (Figure 2), connect the structure to the real roof: the ridge beam, positioned at the top of the truss, and the purlins, lying directly on principal rafters; two additional orders of elements are then placed on the ridge beam and on the purlins: these elements, including secondary rafters, finally support the roof covering, made of planks and tiles.

Often the truss members are subject to degradation phenomena generally due to aging and/or to the prolonged lack of maintenance: damage, disconnections or loss of continuity in the wood fibers may be evident during inspection. Specifically, causes of deterioration may consist of biological agents, due to the organic nature of the material, and weathering factors. The biological degradation is mainly represented by the caries of the wood or by the attack of xylophagous insects.

All these sorts of degradation, that can be usefully assessed e.g. by infrared spectroscopy [1], can lead over time to a change in the mechanical properties of the material, with a consequent reduction in the static efficiency of truss members. Hence, a deep evaluation of the stress state within each single component is therefore necessary to establish, even in the absence of current evident signs of deterioration, the reliability of the whole structural system. In particular, among the truss elements, the tie beam needs to be examined in greater detail, being a crucial component of the system, designed to almost completely absorb axial tensile stresses. On this particular element of the truss, a proper discretization is accomplished in the present work by means of solid FE modeling, capable of acquiring, as a result of an appropriate validation, a more accurate precision in the outcome.

STRUCTURAL DATA AND MODELING

In this work a pre-existing spruce timber truss, located in the Lombardy region and used for a classic pitched roof of the beginning of 20th century, is analyzed. It is a structural system with a wide span length (12 m), and an equal value of 12 m for the interaxle spacing. The system is also very low (2 m high), thus giving rise to high stresses both in the rafters and in the tie beam. Among the higher-order elements, the purlins are in number of 5. The geometric properties of square cross sections for the various elements are: 0.40 m for the cross section side of rafters and tie beam; 0.30 m for struts, king post, purlins and ridge beam; 0.25 m and 0.15 m for the cross section side of the other higher-order elements.

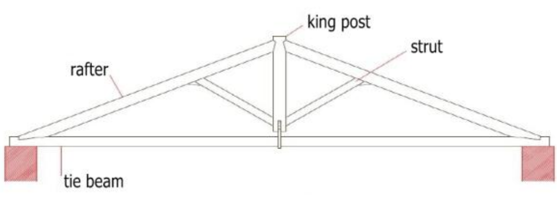

Figure 1: Geometry of the timber truss analyzed

Figure 2: Sketch of roof structure with higher-order elements

The wooden material is assumed to have the following mechanical properties: a tensile strength parallel to the fibers equal to 17 MPa; a compression strength parallel to the fibers of 23 MPa; modulus of elasticity parallel to the fibers and orthogonal to the fibers equal to 11.71 GPa and 4.94 GPa respectively **[2]**; density, mean value = 450 Kg/m^3.

Load analysis is carried out on the real system in the current situation, taking into account all the self weights, both structural and relevant to the roofing, as well as the snow load, assessed according to Italian regulations applicable to the location area. The loads acting on the structure from the purlins up to the roof are translated into point loads acting on the rafters, and added, in view of structural analysis, to all the remaining self weights.

The truss restraints to the masonry are modeled as a pin support on one side and a roller support on the other, thus allowing the tie beam to deform freely along its axis. Each connection between truss elements is modeled by a pinned joint. The distance of the lower end of the king post from the tie beam is assumed, under conditions of undeformed structure, to be equal to 0.20 m, while its self weight is represented by means of a single point load applied to its center of gravity. The loading pattern used for structural modeling and subsequent FE analysis is shown separately in Figure 3a and 3b for point and span loads. With respect to these schematic figures, a correction to the position of the joint connecting king post and struts has been successively made for FE analysis, in such a way to reproduce the actual geometry of the structure examined.

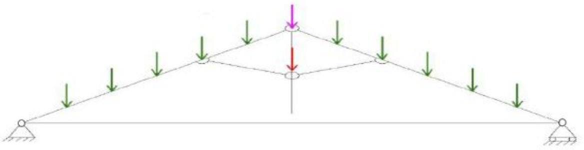

Figure 3a: Point loads acting on the truss structure

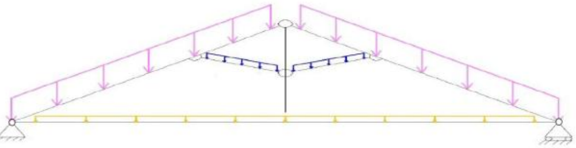

Figure 3b: Span loading pattern on the truss structure

Two types of FE discretization are considered in this paper for structural analysis. A first one takes into account the system as entirely composed of 2-node *Frame* elements, i.e. simply linear elements that coincide with their axis. A second scheme instead provides, for the tie beam only, a discretization based on 8-node *Brick* solid elements: this allows, in addition to a validation of results obtained from the first model type, the evaluation, in future studies, of possible reinforcements [3] [4] [5] for the tie beam; in fact, only through a model that takes into account the actual cross section of such a beam, it is possible to proceed with a geometric description and a subsequent FE analysis that includes the reinforcement portion.

FE analysis by *Frame* elements only

For the example considered and for the first type of discretization, joints corresponding to the position of point loads of Figure 3a are introduced in addition to the end joints of the structural elements composing the truss. A central joint in the tie beam is also introduced, so as to be able to evaluate the displacement due to bending.

Figure 4 reports the deformed configuration under the effect of the loading patterns considered. Actually, the examination of numerical values for displacements shows how the lower extremity of the king post does not reach the central joint of the tie beam, differently from what appears roughly in the graphical representation: in fact, the tie beam remains subject to bending stress due to the effect of its self weight alone.

Figure 4: Deformed configuration of the truss analyzed by *Frame* elements only

Figures 5a and 5b show the axial force and the bending moment diagrams for the structure being analyzed by FE. Numerical results, in particular, provide for the tie beam a constant tensile force equal to 712 kN and a maximum bending moment, almost imperceptible by graphical representation, of only 13 kNm: which gives rise to a maximum normal stress of 5.66 MPa along the beam axis. As regards the rafters, the resulting maximum compression force is equal to 777 kN, while the maximum bending moment at their intrados is 105 kNm, giving rise to a maximum normal stress in the direction of their axis slightly lower than the one obtained in the tie beam, i.e. of about 5 MPa. The internal forces in the king post and the struts appear instead very low and, especially for bending, visible only by a numerical control: in particular, the king post is only weakly stretched, while the struts, subject to limited compression, are only slightly bent.

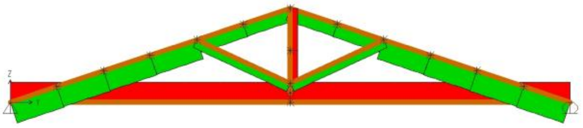

Figure 5a: Axial force diagram via FE analysis by *Frame* elements only

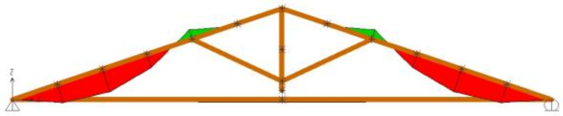

Figure 5b: Bending moment diagram via FE analysis by *Frame* elements only

The FE analysis based on *Frame* elements only represents a starting point for a subsequent comparison to results obtainable by a more detailed model, which introduces, as shown in the following paragraph, a discretization of the tie beam based on solid *Brick*-type finite elements: this, in order to highlight more precisely the stress variability within its cross section and, besides, to allow possible implementations of the model for a supposed reinforcement intervention.

FE analysis by *Frame* and *Brick* elements

In this second type analysis the *Frame* elements are retained on all components of the truss with the exception of the tie beam, which is discretized into 8-node *Brick* solid elements. The discretization of the structure is shown in Figure 6a, in the deformed configuration deriving from the analysis. The high number of *Brick* elements represents an intentional choice, in view of the opportunity to capture even the slightest stress variations within the various portions of the element.

The connection between the *Frame* elements belonging to the rafters and the *Brick* elements discretizing the tie beam has been modeled by introducing an additional *Frame*-type element, arranged perpendicularly to the plane of the truss and connected to the rafter by a hinge; besides, this dummy element is then connected fixedly to the two central *Brick* elements of the tie beam mesh (Figure 6b).

In relation to the data reported in [2] and to the specific FE analysis software adopted, three different Poisson coefficients, taking into account the material orthotropy, are introduced for the solid 8-node elements. These coefficients can be described, for the spruce timber considered, by the vector {0.041, 0.033, 0.35}. Similarly, a vector {11.71, 0.83, 4.94} of Young moduli along three different directions is introduced. Both vectors are assigned in accordance with the sequence prescribed by the specific FE software.

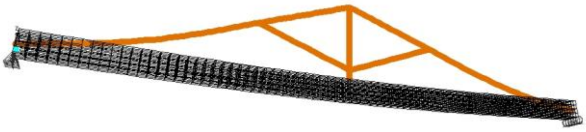

Figure 6a: Deformed configuration of the truss analyzed by *Frame* and *Brick* elements

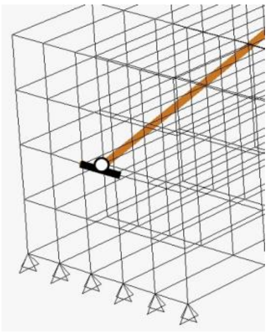

Figure 6b: Connection model between the rafter and the tie beam

Figures 7a and 7b show the axial force and the bending moment diagrams on *Frame* elements. As regards the rafters, the resulting maximum compression force is equal to 774 kN, while the maximum bending moment at their intrados is 107 kNm, giving rise to a maximum normal stress in the direction of their axis of about 5.2 MPa. With respect to the analysis performed as described in the previous section, these values are slightly different, however, with a percentage error that is acceptable and presumably due to the model necessarily adopted for the rafter/tie beam connection above described.

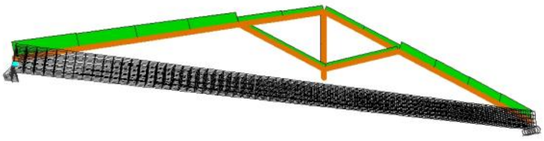

Figure 7a: Axial force diagram on *Frame* elements via FE analysis by *Frame* and *Brick* elements

Figure 7b: Bending moment diagram on *Frame* elements via FE analysis by *Frame* and *Brick* elements

In regard to the tie beam, the results, expressed directly in terms of stress, are reported in Figures 8a and 8b. In particular, Figure 8a describes the normal tensile stresses in the direction of the beam axis: as highlighted in the chromatic scale, they are all included in the interval 3.5 - 7 MPa, denoting values trivially almost constant along the tie beam. Actually, their maximum numerical value, located around the midpoint of the beam, is equal to 5.64 MPa, a value almost coinciding with the outcome deriving from FE analysis by *Frame* elements only. Figure 8b, instead, describes the Von Mises stress distribution, which also takes into account the stress due to the shear effects. The ranges for this distribution appear more differentiated in comparison to those relevant to normal stress, showing decreasing values by proceeding from the bottom to the top edge of the beam, while the maximum estimate at the midpoint is only slightly higher than the maximum normal stress (5.65 MPa): this could have also been anticipated by the numerical values obtained - from FE analysis by *Frame* elements only - for the shear force, giving a maximum equal to only 4kN.

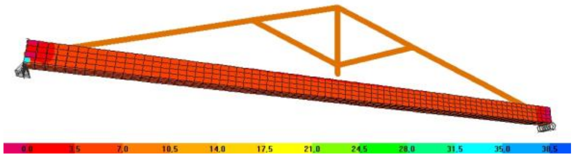

Figure 8a: Normal stress on *Brick* elements of the tie beam, in the direction of its axis

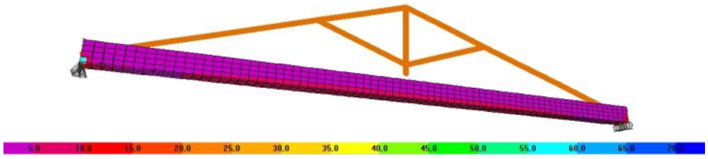

Figure 8b: Von Mises stress on *Brick* elements of the tie beam

ANALYSIS OF RESULTS AND CONCLUDING REMARKS

The comparison between results obtained through the two types of analysis provides a mutual validation for the models adopted. Consequently, the discretization of the tie beam based on solid FE may be usefully employed, in further developments, with the aim of introducing a possible reinforcement at its intrados. In previous works [6] [7], for example, the case of FRP fabrics applied to the lower edge of a simply supported wooden beam was examined.

Particularly, as regards the truss analyzed in this paper, the stress at the lower edge of the tie beam - a critical element for the correct functioning of the entire structure - shows acceptable values in terms of structural safety; however, any possible degradation condition, due to biological or environmental agents - hence to be examined in greater detail through specific instrumental analyses - could have altered the mechanical properties of the wood, making it necessary to apply a reinforcement.

Further, as for what concerns the large number of *Brick* elements used for the discretization of the tie beam, definitely high for the purposes of this work, it can be essential in order to arrange the model for the application of various types of reinforcement, with variable configurations along the element: for this purpose, the input file for FE analysis has been generated automatically through an appropriate computer code, realized in such a way as to allow rapid parametrization of the model.

ACKNOWLEDGEMENTS

Support by the Ministry of Education, University and Research is gratefully acknowledged

REFERENCES

[1] Sandak, A., Sandak, J., Riggio, M., 2016, "Assessment of wood structural members degradation by means of infrared spectroscopy: an overview", *Structural Control and Health Monitoring*, 23, pp.396–408.

[2] Piazza, M., Tomasi, R., Modena, R., 2005, "Strutture in legno. Materiale, calcolo e progetto secondo le nuove normative europee", Ed. Hoepli (in Italian).

[3] Tingley, D., Kent, S., 2001, "Structural Evaluation of fiber reinforced hollow wood beams", 2001 IABSE Conference, International Association For Bridge And Structural Engenneering, Lahti, Finland.

[4] Borri, A., Corradi, M., Speranzini, E., 2001, "Travi in legno rinforzate con barre o con tessuti in fibra di carbonio", *L'Edilizia*, Editrice De Lettera, 8–9, XV, Milano, pp. 48–56 (in Italian).

[5] Borri, A., Corradi, M., Grazzini, A., 2005, "A method for flexural reinforcement of old wood beams with CFRP materials", *Composites*, Part B: Engineering, 36 (2), pp. 143-153.

[6] Carino, C., Rinallo, L.M.A., 2014, "Analisi di una trave lignea inflessa rinforzata mediante tessuti in FRP", Collana rapporti scientifici, Dipartimento di Ingegneria Civile e Architettura dell'Università di Pavia, Anno Accademico 2013/14 (in Italian).

[7] Carino, C., Carli, F., 2016, "Finite Element Analysis of a Spruce Timber Beam Reinforced by FRP Fabrics", *International Journal of Applied Engineering Research*, ISSN 0973-4562, Vol. 11, n.9, pp. 6731-6735.