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Spruce Timber Trusses of Existing Pitched Roofs: A Reinforcement Study

Claudio Carino and Fabio Carli

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

E-mail: carino@unipv.it, fabio.carli@unipv.it

Abstract

A load-bearing timber truss of an existing pitched roof, located in Northern Italy, is examined in this paper by means of finite element analysis, with two possible configurations: the first one, without any reinforcement, that provides, given the assigned loads, barely allowable stress values in terms of current safety standards; the second one, with the application of fiber-reinforced polymeric fabrics on the bottom edge of the rafters and the tie beam, which results in a substantial reduction both in stress and strain. In particular, it is possible to observe a stress migration from the wooden material to the fabric, which is able to produce more satisfactory stress values within the entire structure, thanks to the exploitation of the tensile strength granted by the reinforcement.

Keywords: Pitched roof, Timber truss, FRP reinforcement, Finite element analysis

INTRODUCTION

A particular historical, architectural and cultural heritage is existing in Italy, unfortunately destined - if abandoned - to disappear, but for which a static and functional recovery is still possible, while respecting its identity values: in Lombardy alone, there are more than 30,000 rural buildings, generally identified with the name of *cascina* (i.e. farmhouse), abandoned for years. Most of them were built with classic wooden pitched roofs supported in turn by load-bearing timber trusses: historically, in fact, wood has been the typical building material since ancient times and its use remained predominant until the early twentieth century.

Construction wood maintains its mechanical characteristics over time, provided it is properly maintained and used, as demonstrated by the many wooden structures that still exist today. However, degradation phenomena due in general to aging of the materials and/or the prolonged lack of maintenance can lead over time to an alteration of mechanical properties, with consequent reduction of the static efficiency of the individual elements composing the structure. In addition, the increasingly strict regulations in the field of structural safety tend to further exacerbate these problems.

A law has been recently approved by Lombardy Region in order to simplify the bureaucracy concerning the owners of these rural buildings who wish to intervene by recovering and transforming them into houses, agricultural or accommodation structures. Thanks to this rule, the recovery of rural buildings can be recognized as an activity of public interest, for historical, cultural and territorial reasons. The rehabilitation project may also be approved notwithstanding the master plan established by the Municipality: it will be possible to act through very simplified procedures, based on an urban regeneration principle, with important reductions also in the urbanization charges, provided that the recovery does not involve the medium and large commercial distribution or buildings for industrial destinations, so as to safeguard the historical aspects concerning these structures.

According to this law, which can be framed in a regional strategy for the reduction of land consumption, recovering the existing structures would become more advantageous than building new ones, thanks to the bureaucratic streamlining (for example, in case of changes in use) and to other benefits aiming at more convenient rehabilitation projects. Therefore, the real estate assets could also represent a lever for territory development, if properly enhanced.

This work intends to focus - from a structural point of view - on the recovery study of existing wooden pitched roofs, located in Northern Italy and based on a classic pattern of aged timber trusses [1]. Firstly, a numerical simulation is carried out on the existing structural system and, subsequently, on the same system reinforced by thin fabrics made of fiber-reinforced polymeric (FRP) material [2] [3] [4]. A truss structure with a wide span length and an ample interaxle spacing is taken into account, with the aim of significantly reducing, by the reinforcement, the stress values within the individual elements.

THE WOODEN ROOF EXAMINED

Most of the roofs of rural buildings located in Northern Italy are supported by wooden trusses, capable of eliminating almost completely the horizontal thrusts of the main inclined elements (principal rafters), thanks to the presence of the horizontal element (tie beam). In addition to these main elements, the king post is a typical component of the wooden truss, a vertical element that connects all the other elements, with the exception of the tie beam, although being partially linked to that component by means of a U-shaped iron (bracket). The struts, besides, are elements with an inclination opposite to the obliqueness of the rafters, which transfer their compression force to the king post.

In such a structural system, the tensile axial forces are mainly absorbed by the tie beam; the king post is weakly stretched, the struts are slightly compressed, while the rafters are subject to compression and bending due to the loads coming from the entire roof. Actually, even the tie beam is subject to a weak flexural component, due to its non-negligible self-weight.

The truss acts as a supporting structure for the entire roof: other secondary beams perpendicular to the truss structure are placed on it (in particular, the ridge beam is positioned at the top, while the purlins rest directly on the rafters). A classic roofing pattern widely used in Northern Italy is shown in Figure 1 [1], where two additional orders of elements, including secondary rafters, are placed on the ridge beam and on the purlins, finally supporting the roof covering, made of planks and tiles.

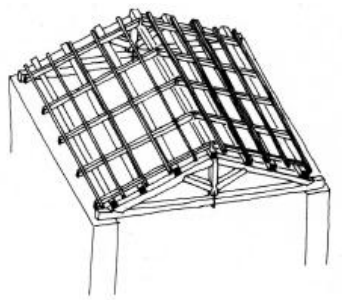

Figure 1: The classic wooden roofing pattern widely used in Northern Italy

According to the sketch of Figure 1, the Lombard truss already examined in [1], made of spruce and used for a classic pitched roof of the beginning of the last century, is considered in this work, but studied by means of a different and more complex model. It is a wide span structural system (12 m), which repeats itself at an ample distance, equal to its span length, and it is very low (2 m high), thus giving rise to high stresses both within the rafters and the tie beam.

The purlins, which rest orthogonally on the truss rafters, are 5 in number. The section properties of the various elements along with their material characteristics [1] [5] are reported below:

- Cross section side of tie beam and rafters = 0.4 m
- Cross section side of struts, king post, purlins and ridge beam = 0.3 m
- Cross section side of higher-order elements = 0.15 ÷ 0.25 m
- Tensile strength parallel to the fibers = 17 MPa
- Compression strength parallel to the fibers = 23 MPa
- Modulus of elasticity parallel to the fibers = 11.71 GPa
- Modulus of elasticity orthogonal to the fibers = 4.94 GPa
- Density, mean value = 450 Kg/m^3

Load analysis of the truss structure is carried out by taking into account every self-weight, both structural and related to the roof covering, as well as the snow load, assessed according to current regulations, for an assumed structure located at an altitude less than 200 m. All the roofing loads are expressed as point loads acting on the rafters, to be added to all the truss self-weights.

The distance of the lower end of the king post from the tie beam is assumed, in the undeformed structure, to be equal to 0.20 m. For the purposes of structural analysis, carried out by a finite element (FE) software package of common use, the truss restraints to the load bearing 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 under tensile axial forces. The king post's self-weight is represented by means of a single point load applied to its center of gravity and is equal to 0.73 KN. The concentrated loads transmitted by the roof covering through the purlins are equal to 62.8 KN, while the one deriving from the ridge beam is of 4.8 KN; span loadings due to the self-weight of rafters, tie beam and struts are computed by FE software, given their section data. Each connection between truss elements is modeled by means of a pinned joint.

FE ANALYSIS OF THE EXISTING STRUCTURE

A first analysis is carried out on the existing truss, which takes into account a discretization into solid elements of the 8-node *Brick* type for the tie beam and the rafters: this, in order to arrange the model in view of the subsequent application of reinforcement to such components [4]; in fact, only by a mesh that allows for their actual section, it is conceivable to proceed with a geometric modeling and a subsequent analysis of a possible reinforcement portion applied to one or both these main elements of the truss. The king post and the struts, namely the least stressed elements of the structural system, are instead modeled as simple 2-node *Frame* elements coinciding with their axis.

The large number of *Brick* elements used for the discretization of both the tie beam and the rafters represents a desired choice, in view of the opportunity to grasp even the slightest stress variations within the various areas of the elements. The discretization model of the structure is shown in Figures 2a and 2b for the undeformed and the deformed configuration deriving from the analysis, respectively. In the same figures, the pin and roller supports are schematized at the ends. Some suitably located joints in the rafters' mesh are exploited as application points of the concentrated loads transmitted to the system through the purlins.

The connection between the *Brick* elements belonging to the rafters and the tie beam has been modeled by introducing additional *Frame*-type elements, of very short length, respectively lying on the intermediate surface of the rafters and on the end section of the tie beam (Figure 3a). Similarly, the rafter/rafter connection has been modeled by means of *Frame* elements lying on the aforementioned surface (Figure 3b). These dummy elements and their relevant connections have been studied in order to introduce a pinned joint between the main elements of the truss, thus reflecting the rotations allowed inside most of the existing timber trusses.

As regards the solid 8-node elements, material orthotropy is taken into account through 3 Poisson coefficients, described, for the spruce timber considered, by the vector {0.041, 0.033, 0.35} [5]. In addition to elasticity moduli described in the previous section, a further one, in radial direction and equal to 0.83 GPa [5], is also introduced, thus giving rise to the vector {11.71, 0.83, 4.94} of Young moduli. Both these vectors are assigned, for the purposes of assembling the stiffness matrix, in accordance with the sequence prescribed by the specific FE software adopted.

Analysis of results, as regards the tie beam and rafters, is accomplished on stress outcomes. For a better view within the graphics, results are depicted separately for these main elements. In particular, Figures 4a and 4b show the normal stress distribution in the direction of the element axis, with a maximum tensile value at the midpoint of the tie beam of 5.5 MPa and maximum values of tensile and compression stress in the rafters of 5.4 and 13.5 MPa at the intrados and the extrados respectively.

Figures 5a and 5b, instead, describe the Von Mises stress distribution, which also takes into account, as well known, the stress due to the shear effects. In the tie beam, where the shear force is certainly very low, these values remain substantially similar to those obtained for normal stresses, while, in the rafters, conversely, they reach a peak of 15.3 MPa at the top edge. The stress concentration detected at the rafter/tie beam connection, which seemingly produces peak values, is actually due to the necessarily approximate model introduced to simulate the presence of connecting hinges.

The stresses reported show barely acceptable estimates in comparison with yield values peculiar to the material, even if suitably reduced according to current standards. However, any potential deterioration condition, due to biological or environmental agents - and to be accurately assessed through specific instrumental tests [6] - could have altered the mechanical properties of the wood, hence drastically reducing its tensile and compression strength values: therefore, the application of a reinforcement appears to be necessary in order to reduce stress outcomes. In addition, a strict application of recent Italian regulations for timber structures urges more severe restrictions in terms of safety checks.

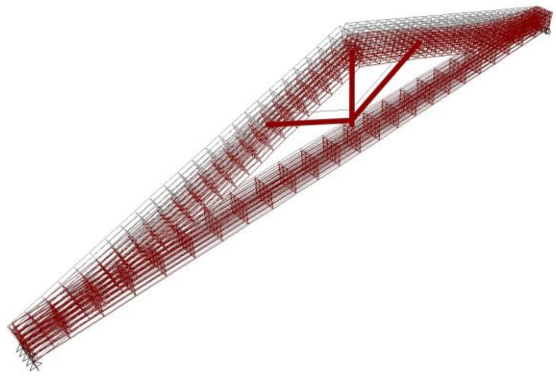

Figure 2b: Deformed vs. ghost configuration following FE analysis

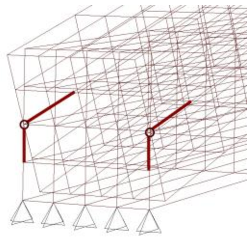

Figure 3a: Connection model between the rafter and the tie beam

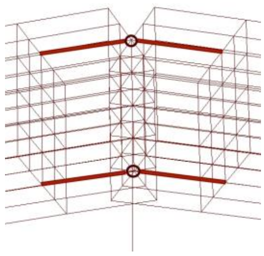

Figure 3b: Connection model of the rafters to each other

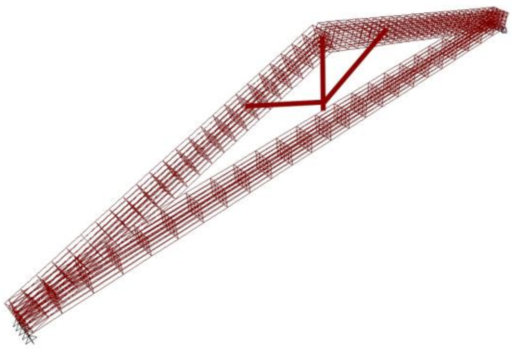

Figure 2a: Undeformed configuration of the truss with *Brick* and *Frame* elements

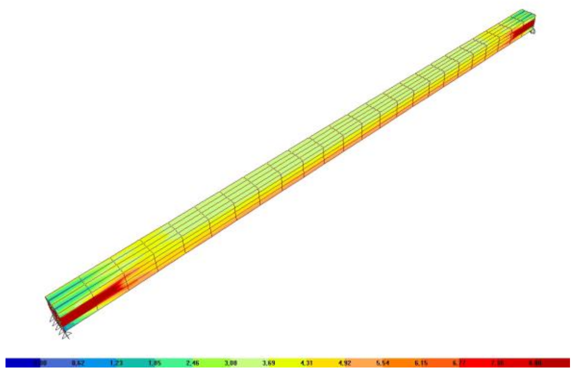

Figure 4a: Normal stress on *Brick* elements of the tie beam, in the direction of its axis

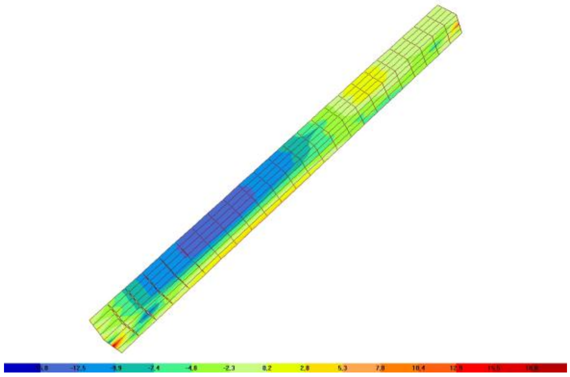

Figure 4b: Normal stress on *Brick* elements of the rafter, in the direction of its axis

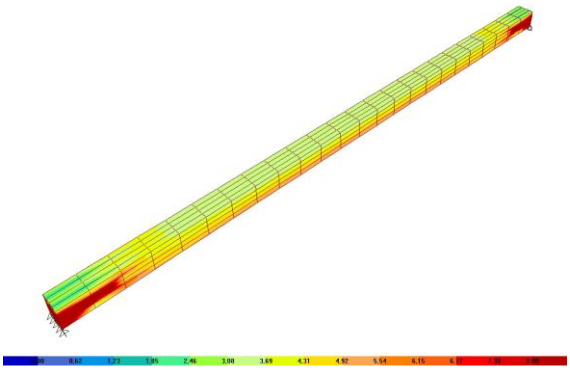

Figure 5a: Von Mises stress on *Brick* elements of the tie beam

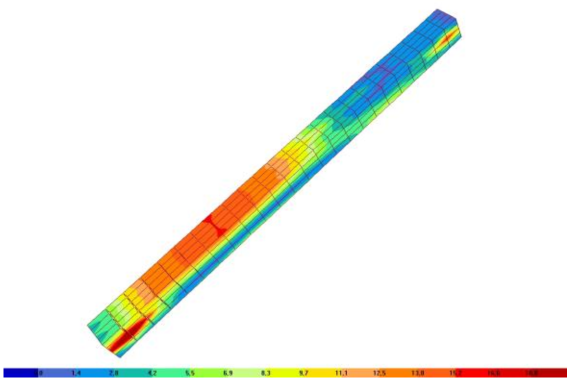

Figure 5b: Von Mises stress on *Brick* elements of the rafter

TRUSS REINFORCEMENT AND FE ANALYSIS

FRP fabrics

In the field of structural reinforcement, fabrics are probably the most widespread form of use of FRP materials. They are made according to an almost infinite range of configurations and characteristics, depending on the materials used and the arrangement of the various bundles of fibers that constitute the fabric.

In FRP-reinforced timber structures, the goal is to provide the system components with greater strength and stiffness, particularly in the areas of the structure subject to tensile stress, for which the wooden material is able to offer limited resistance. The FRP most widespread use is therefore related to the reinforcement of timber components in bending [2][3][4]. It is also worth noting that the association of wood with fiber-reinforced polymeric materials is particularly favorable in terms of compatibility and complementarity: wood lightness, for example, is absolutely not affected by an FRP reinforcement intervention; moreover, the aesthetics of a reinforced element can be easily preserved through a simple masking, obtained by covering the FRP fabric with a thin layer of the same wooden material constituting the structure.

Modeling and analysis of the reinforced truss

The structure examined in this paper, already assessed - as previously described - with reference to its current configuration, is then analyzed by introducing an FRP-fabrics based reinforcement placed at the bottom edge of the tie beam and the rafters. The fabrics are supposed to be glued to the wooden material by epoxy adhesive, assumed to have mechanical properties similar to those of the fiber-reinforced material, and whose thickness is therefore considered to be incorporated into a single whole. The ultimate goal is to achieve a reduction, as emphasized by a new analysis, of the stresses within the wooden material, while conveying part of them towards the FRP reinforcement. The following mechanical characteristic values are assumed for the fabrics [4]:

- Young modulus = 330 GPa
- Poisson coefficient = 0.2
- Tensile strength = 3500 MPa

During the FE modeling phase, the FRP fabric is discretized in 4-node *Shell* type elements, with a membrane behavior, hence excluding any bending effect. In particular, in order to simulate contact, joints defining such elements are overlaid to the bottom joints of *Brick* elements composing the tie beam and the rafters.

For the purpose of numerical simulation by finite elements, the thickness of the fabrics to be applied to the bottom edge of the tie beam and the rafters has been parameterized, in such a way as to include the thickness of the epoxy adhesive used. Some significant combinations have been considered, represented by the following vectors: {1,0}, {2,0}, {1,2}, {1,3}, {2,3}, where the first digit indicates the thickness expressed in 10^{-3} m of the reinforcement applied to the tie beam while the second digit, if different from 0, denotes the thickness in the same measurement units of the fabrics applied to both rafters; the null digit indicates the absence of reinforcement in the rafters.

Compared to the values obtained for the unreinforced structure, the first two combinations, examined in the absence of reinforcement in the rafters, provide, in percentage terms, rather limited reductions (between 1 and 6%) of tensile, compression and Von Mises stress at the rafter edges, while, since these combinations express a reinforcement directly affecting the tie beam, they produce at its bottom surface reductions greater than 20%. This means that the fabrics applied to the tie beam only, although this is a critical element for the correct functioning of the entire system, is not able to significantly reduce the stress even inside the rafters, which are indeed subject to considerable internal forces due to all the roofing loads transferred to them.

In contrast, combinations {1,2}, {1,3}, {2,3} lead to substantial reductions in stress for both the main components. In particular, the second of the three combinations is able to provide more than satisfactory reductions for the maximum tensile stress in the tie beam (-21%), the maximum tensile stress in the rafters (-66%) and the maximum compression values in the rafters themselves (-16%). At the same time, it is able to contain the costs that the third of the three combinations, while leading to a 73% decrease in tensile stress for the rafters, would entail. Furthermore, the combination {1,3} is able to reduce the maximum vertical displacement in the rafters by about 10%, while, with the reinforcement in the tie beam alone, this reduction would be almost negligible (-2%).

For the combination {1,3}, the normal stress distribution in the direction of each main element axis is shown in Figures 6a and 6b, with a maximum tensile value at the midpoint of the tie beam of 4.4 MPa and maximum values of tensile and compression stress in the rafters below 2 and 12 MPa respectively.

Figures 7a and 7b, instead, describe the Von Mises stress distribution, which also takes into account the stress due to shear effects. These estimates remain for the tie beam within values very close to those found for normal stresses, while in the rafters they reach a peak value of about 13 MPa at the top edge. The stress concentration at the rafter/tie beam connection is due, as in the case of the unreinforced structure, to the approximate model introduced for the connecting hinge.

Finally, Figure 8 shows the Von Mises stress distribution within FRP *Shell* elements only, both in the tie beam and in the rafters. The figure this time shows the truss in its entirety. It can be observed by the analyses that the reinforcement has fulfilled its main task of reducing the stress values in the wooden material, yet reaching within itself still far estimates compared to allowable ones: 230 MPa in the rafter reinforcement and about 125 MPa in the fabric glued to the tie beam.

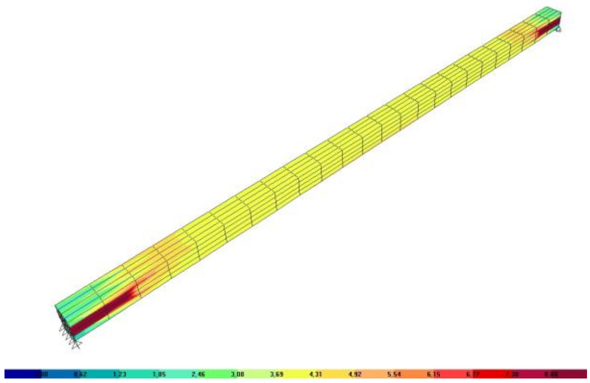

Figure 6a: Normal stress on *Brick* elements of the reinforced tie beam, in the direction of its axis

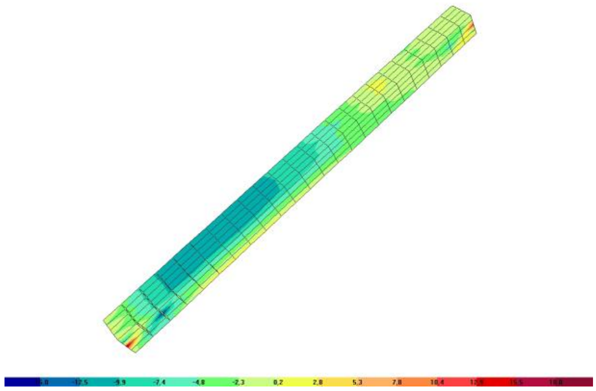

Figure 6b: Normal stress on *Brick* elements of the reinforced rafter, in the direction of its axis

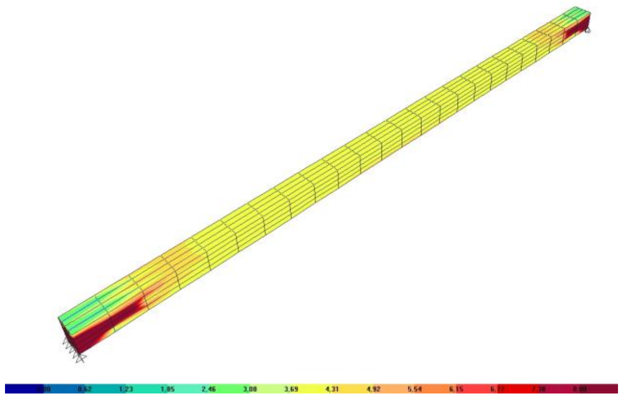

Figure 7a: Von Mises stress on *Brick* elements of the reinforced tie beam

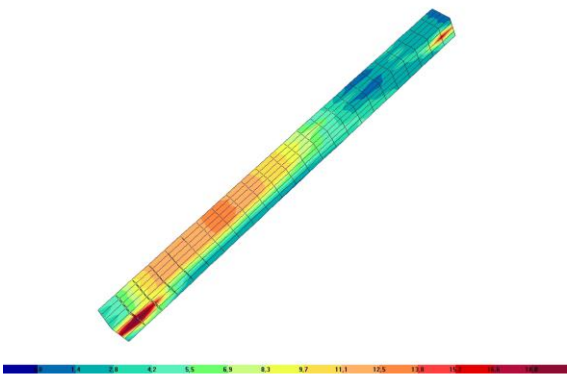

Figure 7b: Von Mises stress on *Brick* elements of the reinforced rafter

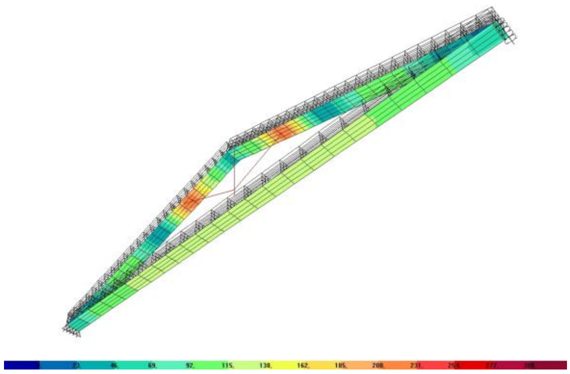

Figure 8: Von Mises stress distribution within the reinforcement fabrics only

CONCLUDING REMARKS

With reference to the existing timber truss examined in this paper, the stress distribution within the main components of the entire structure - namely the tie beam and the rafters - shows barely acceptable values with regard to a safety check; however, any presumed deterioration condition, due to biological or environmental factors, might have been enough to alter the mechanical properties of the wood, making it necessary to apply a reinforcement.

As already shown in a previous work with reference to a simple bent timber beam [4], a reinforcement based on the use of fiber-reinforced polymeric fabrics and applied to the bottom edge of the structural element is able to provide satisfactory results in terms of significant reductions of stress and strain. In particular, for the truss examined, a thinner reinforcement applied to the tie beam and a more substantial one - yet still visibly contained - at the intrados of the rafters, give rise to a considerable decrease both in stress values and in maximum displacements. Therefore, while yielding a significantly moderate impact on the original structure - compared to other more invasive types of reinforcement [7] - this intervention is able to admit rapid structural reuse in compliance with current safety standards.

The model studied in the present work, essentially based on the use of *Brick* and *Shell* finite elements for the portions of the wooden and the fiber-reinforced materials respectively, appears to be particularly suitable in view of arranging various solutions for the reinforcement configuration - also variable along each element - with the aim of optimizing results: for this purpose, an appropriate computer code has been developed capable of generating in parametric form the input file for FE analysis.

ACKNOWLEDGEMENTS

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