SHATIS'17
4th International Conference on
Structural Health Assessment of Timber Structures
20-22 September 2017 Istanbul, Turkey

A DATABASE CONSTRUCTION TOOL FOR SEISMIC VULNERABILITY ASSESSMENT OF TIMBER ROOF STRUCTURES

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Keywords: Timber roofs, Seismic Vulnerability, Assessment, Inspection database

Abstract

A procedure for the assessment of the seismic vulnerability of timber roof structures previously proposed by the authors is divided into two steps: the first consists in acquiring knowledge of the structure by means of a visual inspection focusing on aspects related to seismic behaviour, while the second elaborates these data to express the vulnerability level of the structural system. Reference is made to a series of structural characteristics and details that may be considered as vulnerability indicators, among which are the structural typology, the quality of carpentry joints, and the effectiveness of restraints. The original implementation of the procedure made use of paper forms, or templates, for the phase of data collection. The template permits to organize data in a format suitable for use in the vulnerability assessment step, but is also useful as a guide for performing the survey according to predefined and standardized criteria. The survey site conditions, however, are often unfavorable, due to the location of roof structures that may be difficult to reach, with poor environmental and operative conditions, limited access possibly lacking a planking level, dust and subdued light. Paper forms, even if resilient, are often cumbersome to bring along and fill. The development of new digital technologies, like easily portable computers of small weight and limited dimensions and tablets, has suggested developing a revised digital version of the procedure. The design and implementation of a software tool guiding the survey and recording the observed data into a database has brought to update and improve the original procedure, taking advantage of the possibilities offered by a software support that combines programming language and graphics with great flexibility. The newly developed features of the current prototype system are presented and discussed by means of examples for typical roof structures of the Italian constructional tradition.

1 INTRODUCTION

The many earthquakes that struck Italy in the last decades, from the 1970's up to the most recent one of Central Italy 2016-2017, have shown that the response for traditional masonry buildings is significantly influenced by the behavior of the timber roof structure. The frequent cases of damage related to failure of the roof system or to its interaction with the walls has been counter-balanced by other more positive situations. These corresponded to well-organized and interconnected roof trusses, sometimes strengthened with light interventions, that neither disassembled nor collapsed, but rather kept well-connected with walls, contributing to link them and create a collaborative behavior in the whole building, which is most times the discriminating factor in the final outcome.

This consideration has inspired a research project devoted to timber roof structures under seismic action [1, 2]. The major aim was at investigating the causes and the conditions that would result in seismic vulnerability of the timber roof structure. A parallel objective was to identify simple but effective improvement interventions that could reduce a high vulnerability level [3]

More in general, the work was expected to put into evidence the specific issue of the response of roof structures to seismic action. This action, being of dynamic type and usually with a dominating horizontal component, differs radically from the vertical loads for which roof structures were traditionally conceived. In this situation, the vulnerability assessment of timber roof structures must associate an exam of the features typically related to this material with those pertinent to the problem of seismic behavior with its characteristics, demands, and methods. The main result of this project has been the proposal of a procedure for assessing the seismic vulnerability of timber roof structures.

As a premise, it must be remarked that the seismic vulnerability of a structure, intended as its more or less pronounced tendency to undergo damage or failure in an earthquake, may be expressed at different levels of detail. It may be a rapid single rating based on a very synthetic visual inspection of some particular elements, to be used for pointing out emergency situations. Priority interventions may be decided examining different structures on a comparative basis, as in the case of a territorial survey. Otherwise, vulnerability may concern a more detailed exam of the structure, aimed at a more specific definition of possible criticalities with respect to a dynamic action; the exam of the structure carried out at this level is not yet the assessment that is necessary for design purposes if interventions have to be performed, but is at a time sufficiently detailed to address decisions, and sufficiently synthetic to be performed in a limited amount of time. The latter approach has been followed within this research.

The procedure proposed comprises a first step in which a visual inspection of the structure is performed in order to acquire knowledge on its state and collect data to be used subsequently for the actual seismic assessment. The second step consists in analyzing a series of characteristics of the structural system that have been recognized as significant indicators of its capability of seismic response. Each of the indicators, summarized in the following section, is based on the data and information collected in the first step, which is crucial for an effective assessment.

The visual inspection and data collection phase, which is the center of the present work, has been initially carried out by filling an ad-hoc form that lists all the items to be examined and checked during the process in an organized way.

Visual inspection performed with the basis of a structured form has been used since many years for seismic vulnerability assessment campaigns in various countries, and in Italy in particular. These were related to different kinds of buildings and structures, but did not concern timber. The experience derived from these operations has shown the importance of a well-defined form for an accurate and efficient data collection. The form structure actually guides the surveyor performing the visual analysis, driving to examine with special attention the items that are most critical or most useful for the specific purpose.

In vulnerability assessment applications, so far a printed paper form has generally been used. Some exceptions are starting to arise, like the vulnerability assessment forms alternatively proposed by FEMA as a digital tool [4]. These are, however, intended for a risk estimate crossing vulnerability assessment from the building survey and the local hazard level; the digitized procedure therefore includes a rapid survey and a numerical elaboration of the risk, for which a software program is particularly suited.

The very fast development of digital technologies that now propose highly robust and portable hardware, and on the other side the difficulties encountered in many on-site applications of the survey form in its original paper format have brought to design and implement a new digital version of the form. The possibilities offered by a software approach may solve many of the problems met. At the same time, the resulting enhanced flexibility has permitted to redefine and improve some aspects of the procedure. These aspects are presented and discussed in the following.

2 SEISMIC VULNERABILITY ASSESSMENT FOR TIMBER ROOFS

The level of vulnerability of the roof structure is assessed in the second step of the procedure, after visual inspection [5]. The different structural characteristics and conditions that have been considered most significant for their effect on the seismic response are grouped into the following general indicators; each of them may be further detailed and subdivided pointing out different issues to be considered,

1. The conceptual design: this is the first indicator to be considered; most roof structures, in fact, have been conceived with a load carrying function towards vertical loads; the capability to balance horizontal forces like earthquake-induced inertia forces may have not been considered in the original design, or may be possible but limited altogether; it depends on the structural concept adopted; the first vulnerability indicator concerns, therefore, the structural typology [6].
2. The carpentry joints: the type, details, and conditions of carpentry joints are an important factor in determining the vulnerability of the roof structure; the capability of the joints to hold the connection during cyclic conditions that may reduce compression in the timber elements, and their expected post-elastic behavior must be examined, with the purpose to identify possible failure modes, ending in disassembly or brittle failure.
3. The system of constraints: the types and conditions of the connection of the timber structure to the walls may be considered a major vulnerability indicator; it deals with the effectiveness of the connection in preventing sliding off and loss of support; this kind of failure often triggers progressive failure of the whole building system;
4. The state of the structure: any condition specifically related to the state of the structure that may affect vulnerability is considered here, including the maintenance and conservation state, but also the presence and quality of previously performed strengthening interventions.

The indicators are graded according to a scale that ranges from A to D through B and C. The value A corresponds to the minimum vulnerability of a structure that was designed, executed and maintained according to best practice and incorporates all the positive features in favor of seismic safety, comparable to a new code-designed structure. D is the highest vulnerability level, representing a structure with serious deficiencies that should be promptly remediated by suitable interventions, B and C representing intermediate levels.

Support for grading is given in various forms: for some indicators, reference tables have been developed based on experimental or numerical analysis results, or both, for the most frequent situations; others may be judged referring to the same fundamental concepts; for some other indicators, less developed at the moment, results from case studies are reported as examples. The roof structure typology that is most frequent in Italy is composed of a series of trusses interconnected by ridge beam and purlins, or additionally by diagonal struts and bracing elements. The procedure is particularly tailored on these cases.

The purpose of the first step, the visual inspection, is to obtain the information and data necessary to elaborate the indicators, according to the list above. Some considerations stem from this fact,

1. The inspection considers with particular care some features of the structural system and may simplify others that are usually requiring much attention in the general assessment of timber structures; for instance, the determination of the wood species affects results in a very limited manner, while the presence and effectiveness of metal closures of the joints protecting them from load cycles that may cause a pressure decrease is a priority;

2. Old structures not suitable to balance horizontal loads are not rare; occasional horizontal components are usually absorbed by the actual semirigidity of carpentry joints, or other sources of resilience; yet, these situations are characterized by high uncertainty of behavior and are not reliable; they need to be pointed out and corrected as a most important result of the analysis; other points related to the possibility of the structure to respond to the action concern, for instance, the size of the cross-sections that must be sufficient to carry an increased stress level in their current state; degradation and decay must be considered here, being influential on this issue; given the importance of these situations, the layout of the structure and the relevant data are the first examined and collected.

3 VISUAL SURVEY AND DATA ORGANIZATION

The data and observations gathered during the visual survey are written on site in the data collection form that, consequently guides the inspection. This point is important in order both to direct the inspection to the main items of interest for the intended purpose, and to some extent to homogenize the way the survey is carried out over different cases.

The structure of the collection form must be, then, efficient in considering with due care all the important features and in reducing time and the effort as much as possible.

The survey, and the form, has been conceived with a tree structure, where information is searched with increasing detail, basically going from a structural level to the element and then to the joint level.

As a result, a first page gathers general information identifying the building (type, location, period of construction) and describes its general geometry (dimensions, general layout) and material (brick, stone masonry, etc.). Much of this is compiled out-of-site, before or after the survey.

The wood species present in the roof structure are then specified. A simplified estimate is sufficient here. The presence of biotic attack or degradation for mechanical reasons is posted out at this point for a general view. It will be indicated more specifically in terms of amount and location at element description time.

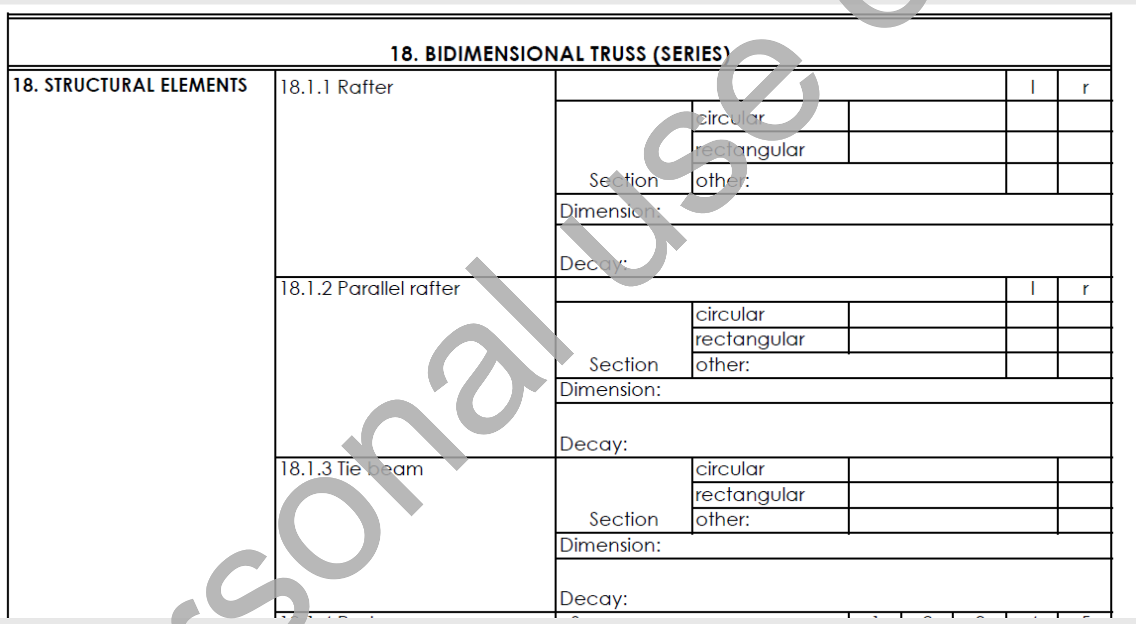
The type and state of the connections between the roof structure and the supporting walls are examined as a third point.

The next set of data concerns the structural typology, that is, the problem of structural characterization- A timber structure may be conceived as two-dimensional, or 2D, (e.g. trusses interconnected by more or less effective linking elements or substructures) or less frequently as three-dimensional, 3D. From this alternative, down-branching brings to examine more details. For a truss system, 2D, the trusses are individually examined in sequence. For each, the main elements are surveyed, as well as the joints connecting them; down-branching applies as well to joint description.

Similarly, the members linking the trusses are examined. A sketch to be drawn at the start permits to identify the location of trusses and other elements by assigning them a number.

Because the visit on site may not be easily repeatable, an estimate of the paper pages to be brought at roof level is necessary. Following the branches down to joint detail for each truss may require a considerable amount of forms and their compilation may result tedious, fostering errors. Figure 1 shows part of a page collecting data on structural elements..

The data collection procedure has been applied to several roof structures, with good results in terms of the objectives, in spite of the inconveniences mentioned above. After a period of application, its implementation into a software tool seemed to be timely.



18. BIDIMENSIONAL TRUSS (SERIES)						
18. STRUCTURAL ELEMENTS	18.1.1 Rafter				l	r
		Section	circular			
			rectangular			
			other:			
		Dimension:				
		Decay:				
	18.1.2 Parallel rafter				l	r
		Section	circular			
			rectangular			
			other:			
		Dimension:				
		Decay:				
	18.1.3 Tie beam	Section	circular			
			rectangular			
			other:			
		Dimension:				
		Decay:				

Figure 1: Excerpt from paper form

4 ADVANCING THE PROCEDURE

The data collection form that guides the vulnerability assessment according to predefined and standardized criteria was originally on paper for a series of reasons, mostly related to the survey conditions. These paper forms have been used until recently in case studies and applications and have been useful in a first period of development also as a tool to test the procedure. Some inconvenience, however, was experienced in their use, especially in the inspection of large roof structures that required to deal with bulky form packs, a situation aggravated by the usually inhospitable under-roof environment. The state of survey sites is often unfavorable, due to the location of roof structures that may be difficult to reach, with poor environmental and operative conditions, limited access possibly lacking a planking level to walk on, great quantity of dust, subdued light, usually with no possibility to connect to power outlets. Paper forms, even if resilient, become often cumbersome to bring along and impractical to fill. At the same time, the adverse site conditions had suggested to avoid using and even bringing on site a normal and usually delicate portable computer.

Highly portable and robust digital tools of small dimensions and weight, with batteries with long lasting charge have seen a fast development, and are now commonly available. In general, the possibilities offered by mobile technology have fostered various projects for computer-based assessment surveys. With reference to timber structures only, the European Union COST project FP1101 (Forest products) has defined a computer-based data collection template for the assessment of the conditions of timber structures. A first version was implemented in [7]. A template for damage assessment of timber structures of modern design had been presented in [8].

The Mondis project [9], based on the use of tablets, aims at implementing a tool for on-site monitoring of monument damage using mobile devices; it is not, however, intended specifically for timber structures.

This fast development of new digital technologies has suggested developing a revised digital version of the visual inspection and data collection step in the vulnerability assessment procedure [10]. The design and implementation of a software tool recording the observed data into a database has brought to update and improve the original process, taking advantage of the possibilities offered by a software support [11] that combines programming language and graphics with great flexibility.

The new system offers advantages of data digitalization on site and the possibility of a more efficient management of branching down in the data collection phase. The interface with the user is by means of menus for the different items to be considered; the chosen option opens up a new screen with data to be inserted and possibly further branching down. As an example, fig. 2 reports the first screen with general building information and the pointers to more detailed information, like “dimensions and geometry” and the like.

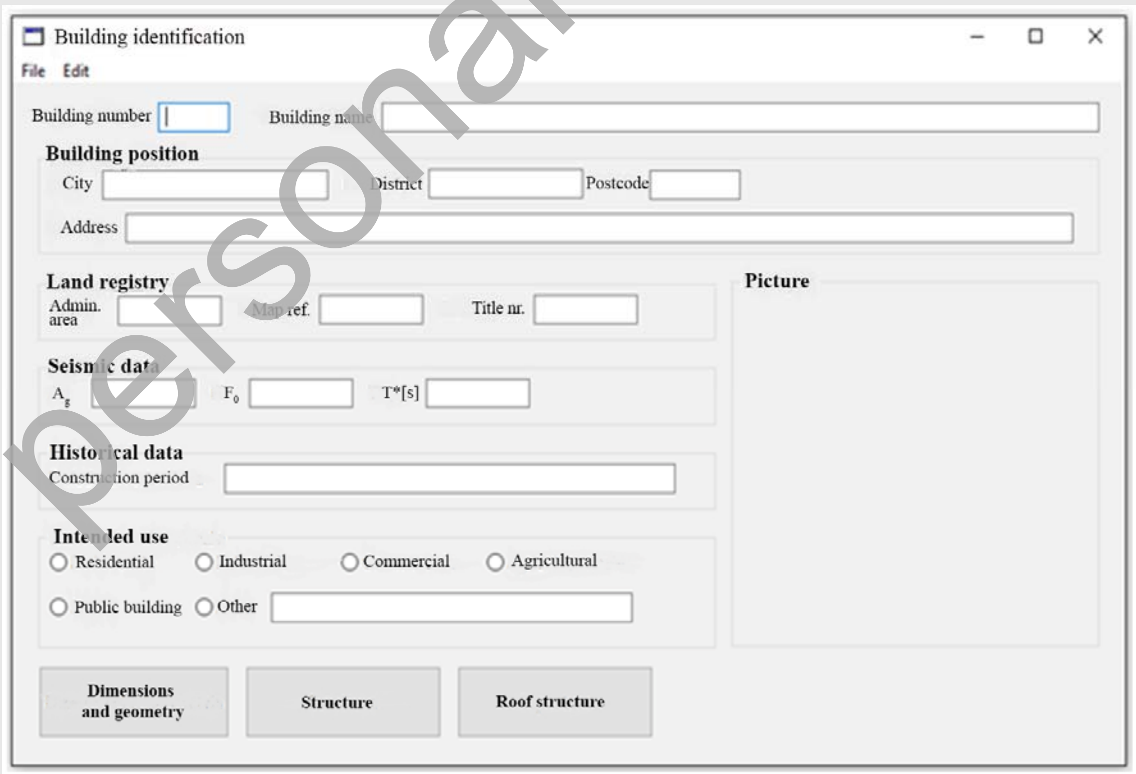


Figure 2: Building information screen

4.1 System implementation

The original data acquisition procedure was organized with a tree-like structure, which is particularly apt to digitalization, and could be easily implemented. In this modality, however, the tree structure may be best exploited with many advantages compared to the original version. In particular, the possibility of

1) moving swiftly along the tree, following down a branch, but also to climb back easily for checking or fixing some information;
2) presenting default values, that may be promptly modified if necessary, simplifying and speeding the process;
3) repeating automatically data for similar elements, intervening only for specific modifications or additions; for instance, if a series of trusses has the same general characteristics, it is possible to define a master truss for which all the data are put in, and generate others, modifying what needed; this operation, as the previous points, is possible also with hard copies, but it becomes extremely time- and paper-consuming; usually paper forms could report the reference case number and only variations, but each form was then partially filled and subsequently completed off-site; errors were likely to occur;
4) inserting new typologies, at different levels (structure types, elements, joints…) which would then appear with the previously defined ones in the menu; this modification of the system is an addition that does not require its total restructuring; this has been the case when, after observing many recurrences, the semi-conical roof structure frequently covering the apse of churches was inserted;

Some other features that are in the development line but are not yet implemented are the possibility of

5) cross checking of entered information, to sort out possible errors;
6) inserting directly sketches, pictures and photos taken at the moment of the survey, that is, on site; now images, as well as comments, documents etc., may be inserted, but usually this is done after the survey; the possibility of taking pictures and insert them with the same instrument will be at best with a tablet or smartphone version of the procedure.

The important general advantage is to obtain directly a database containing in an organized way the data for the case; the database may be accessed by other systems for processing; a module for the evaluation of the indicators, that is, the second step of the procedure is being developed.

The application to practical cases has permitted to test the implemented software and to improve it with some amendments and additions. One of these applications is outlined in the following section.

5 AN APPLICATION

The roof structure of the church of St. Stephen in Vimercate, Milano, in fig. 3, has been used as reference case for testing the new data acquisition procedure.

Figure 3: Views of the church of St. Stephen

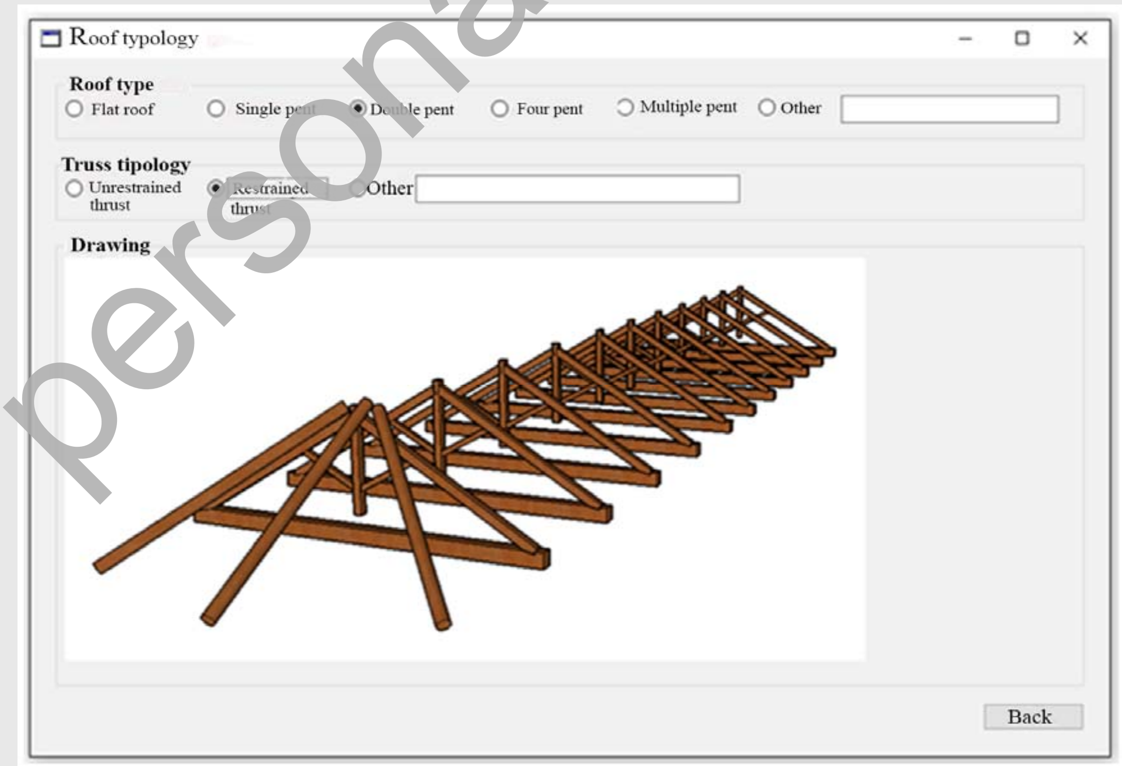
Figure 4: View of the roof trusses

The roof covers the central nave of the church and has a typical configuration of 11 parallel trusses ending in a semi-cylindrical roof over the apse. The trusses are interconnected simply with purlins and a ridge beam, as in fig. 4. The roof structure is not visible from below, because it covers a barrel vault that masks it. Not being considered part of the church architecture but only a functional element to support the roof pents, its construction and detailing are not sophisticated. Roof structures of this type have often been considered an artisan element of secondary importance, not understanding their role in some conditions like seismic actions. Figure 5 shows a detail where rudimental manufacturing is evident.

Figure 5: Detail of the rafter and purlin crossing area

The following figures, 6, 7, and 8, are screenshots from the software system. The first gathers general data on the structure and shows its sketch, which was inserted off-site.

Figure 7 concerns the first truss, used as master for the others. Some information like the type of wood remains at this level, others, like the structural elements, branch down. The rafter menu describing the left and right rafter is in fig. 8; space for notes and comments is available, because some observations cannot be condensed in numbers and measures.



Roof typology

Roof type
○ Flat roof ○ Single pent ● Double pent ○ Four pent ○ Multiple pent ○ Other

Truss tipology
○ Unrestrained thrust ● Restrained thrust ○ Other

Drawing

Figure 6: Screen with structure type information

The description of joints follows from the truss page (e.g. fig. 9). Describing a software application synthetically is not effective, but surely the implementation of this case, and some others not described here, were effective in pointing out advantages as well as some limitations. One was the need to include the apse roof among the available typologies, quoted above.

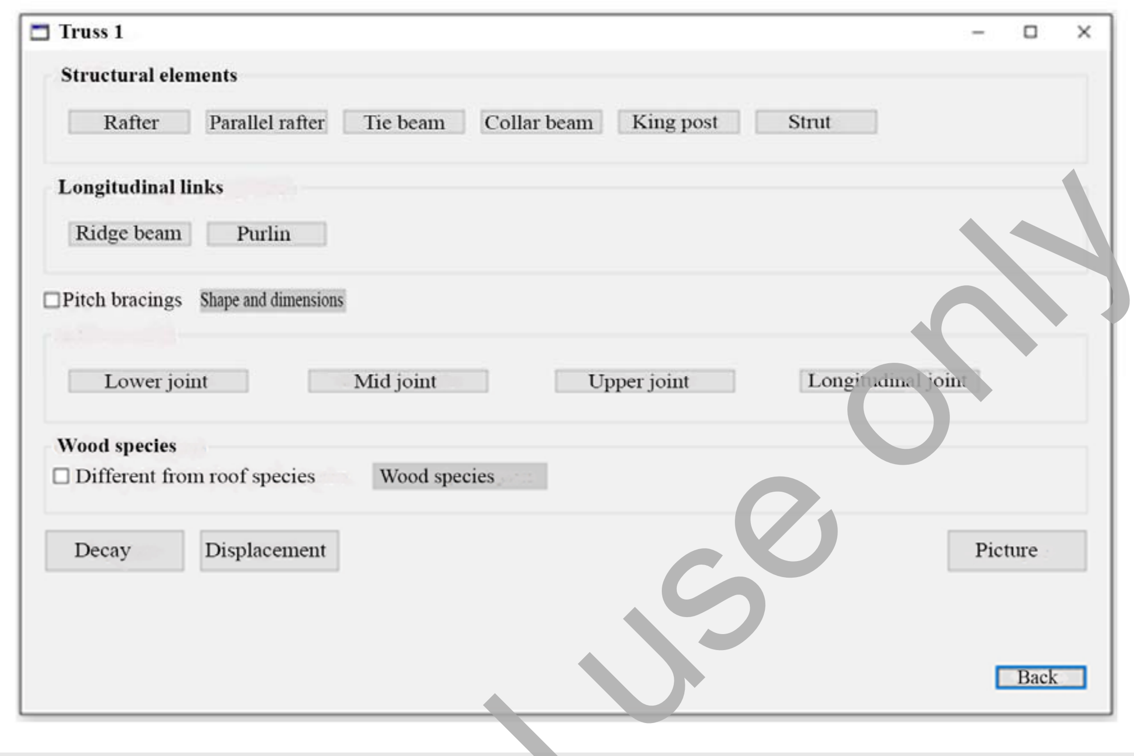
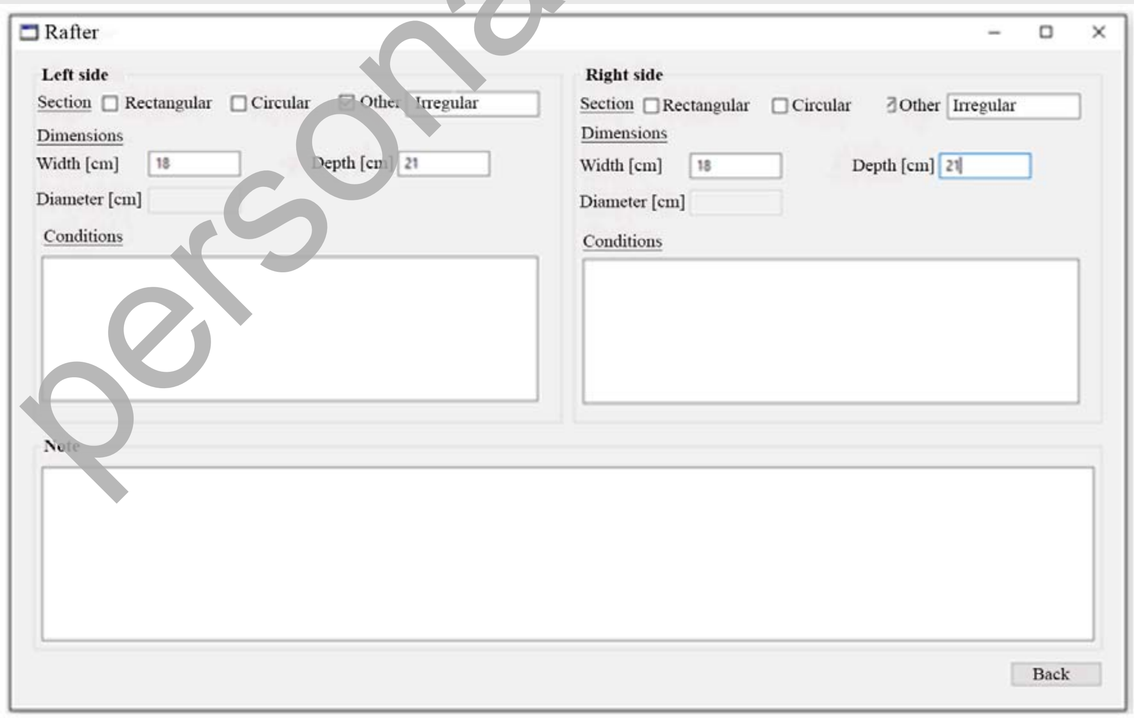


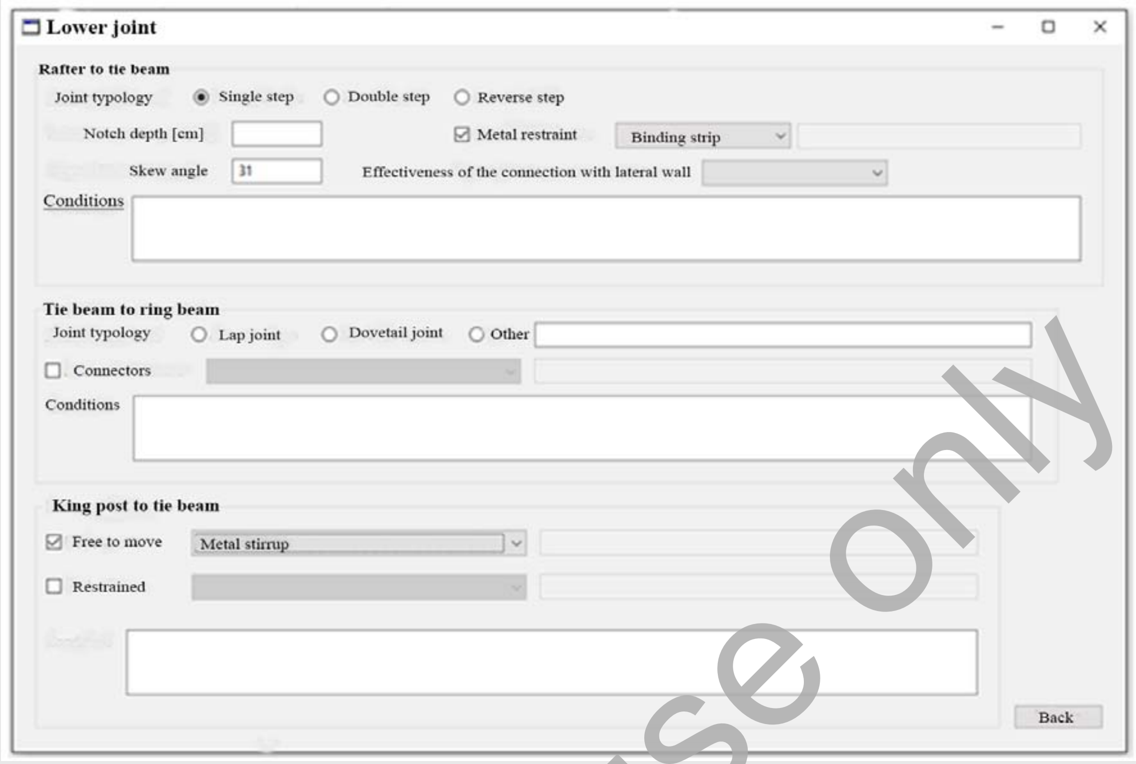
Figure 7: The truss specification with links to its elements



Left side
Section ☐ Rectangular ☐ Circular ☑ Other Irregular
Dimensions
Width [cm] 18 Depth [cm] 21
Diameter [cm]

Right side
Section ☐ Rectangular ☐ Circular ☑ Other Irregular
Dimensions
Width [cm] 18 Depth [cm] 21
Diameter [cm]

Figure 8: Detailing the rafters



Lower joint

Rafter to tie beam

Joint typology ● Single step ○ Double step ○ Reverse step

Notch depth [cm] ☑ Metal restraint: Binding strip

Skew angle: 31 Effectiveness of the connection with lateral wall

Conditions

Tie beam to ring beam

Joint typology ○ Lap joint ○ Dovetail joint ○ Other

☐ Connectors

Conditions

King post to tie beam

☑ Free to move: Metal stirrup

☐ Restrained

Figure 9: Collecting data on lower truss jonts

6 CONCLUSIONS

The seismic vulnerability assessment of a timber roof structure is a challenging task, for the variety of possible situations and for the influence that details may have on the final outcome. The use of a data collection form that guides in performing the survey in a structured manner helps focusing on the items that are most influential on the seismic behavior.

The use of a digital version of the data collection form initially developed on paper has permitted to enhance flexibility in the operation, reducing significantly the compilation time required, as well as transcription errors, a considerable advantage in the often adverse site conditions.

More features need to be added to the first version that has been implemented, among which is the possibility of data cross-checking and the very basic but powerful possibility of inserting directly at survey time photographic material with views and details that are sometimes better described in a graphic manner.

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