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A Database Model for the Analysis and Assessment of Historic Timber Roof Structures

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ABSTRACT

Visual inspection assisted by well-structured forms allows experts to collect homogeneous data in order to report about typical damage/vulnerabilities of structures. This is the basis for deriving vulnerability factors to predict failure mechanisms and identify urgent interventions. A database model with an associated structured form for the assessment of historic timber roof structures has been developed during a two-week Short Term Scientific Mission (STSM) in May 2015 at CNR IVALSA Institute in San Michele All'Adige (Italy). The aim is to assist during inspection in recording all the necessary information and later in analysing data from several inspections, allowing to identify typical damage and its causes. The database model, starting from the work of COST Action FP 1101 and further developed and digitalised during the STSM, has been initially populated with data previously collected by the University of Strathclyde through visual assessment of 29 historic timber roofs in Scotland.

KEYWORDS

Timber, Roof, Structures, Historic, Database Model, Structured Form, Assessment, Diagnosis

1 INTRODUCTION

Visual inspection is the basis of any structural assessment, which is a prerequisite for further analysis, assessment and intervention. Different factors and their interdependency must be considered during the assessment, such as: form, material, loads and environment. The original characteristics and any later alteration/damage must be examined and their causes identified. There are many assessments of single case studies in literature, but their methodology is heterogeneous. The use of structured forms to guide visual inspections can overcome this problem: it provides a uniform approach in the assessment, even when different professionals are involved, thus facilitating comparison of different case studies and identification of vulnerabilities.

Structured forms have been used since 1980s for vulnerability surveys and post-event damage recognition surveys. Benedetti and Petrini's form (1984) was developed to assess the seismic vulnerability of masonry buildings in Italy. More recent research has

produced different types of forms to assess seismic damage (Baggio *et al.*, 2007), to assess causes of failures in twentieth-century timber roof structures (Frese and Blas, 2011; Toratti, 2011; Hansson, 2011) and to assess the seismic vulnerability of traditional Italian timber roof structures (Parisi *et al.*, 2013). In all of these studies the first step was a visual examination of the structures according to a codified procedure: a series of characteristics that determine or influence the specific aspect studied were identified and then a classification criteria was defined to be able to compare different cases, identify urgent interventions and make a plan for risk reduction in the territory.
Toratti's form (2011) was developed with a twofold purpose: to help the experts in the assessment, making them aware of the relevant questions that need answers; to produce uniform results that can be analysed in order to draw conclusions on typical damage and related causes. The form developed by Task Group 1 (TG1) of Working Group 1 (WG1) of COST Action FP1101 (Riggio *et al.*, 2015) had the same purpose but focused on traditional timber roof structures, which had not been addressed so far. Starting from this work a database model and associated form have been developed during a two-week Short Term Scientific Mission (STSM) in May 2015 at CNR IVALSA Institute in San Michele All'Adige (Italy). This paper describes the outcome of this STSM.

2 THE DATABASE MODEL & ASSOCIATED STRUCTURED FORM

2.1 Approach

TG1 identified a series of objectives that the form should fulfil (Riggio *et al.*, 2015):

- Allow collecting a significant amount of data reporting typical damage/vulnerabilities;
- Support multi-level analysis (visual inspection, in-situ tests, lab-tests, etc.);
- Define structural types (considering the European built asset) and a damage taxonomy to provide a unified approach to the evaluation of structural damage;
- Distinguish between material degradation and mechanical damage.

Before the STSM the TG1 form was in word format, which did not allow for the analysis of a big amount of data and was not suitable for quick inspections, due to the considerable amount of pages involved. Moreover, a tree-like organization had been implemented but structure types and damage taxonomy for each level (system, unit, element, connection) had not been clearly identified. The inclusion of Visual Strength Grading regulations (such as UNI, 2004) had to be defined too, and graphics were needed to support the relevant terminology. Moreover the form needed to be validated by applying it to real case studies.
The STSM work focused on the reorganisation of the contents of the TG1 form in both format and structure using Microsoft Access software and data from visual inspections carried out in summer 2014 by ADCRU (Architectural Design and Conservation Research Unit at University of Strathclyde) in 29 timber roof structures in Scotland. The software was chosen because it allows managing and multiple-querying a big amount of data and also because it would allow an easy integration with a mobile phone application being developed in the frame of Working Group 2 of COST Action FP1101 to assist professionals in the selection of interventions on timber roofs (Harte *et al.*, 2015).
Since the data available was related to seventeenth- and eighteenth-century timber roofs in Scotland, it was decided to focus on the development a form for the inspection of historic timber roof structures. Once validated, it will be possible to extend the work to the development of a form for other roof structure types and other load-bearing systems.

2.2 Content

The aim was to organize the form in order to fulfil a twofold purpose, as in Toratti (2011):

- Assist professionals during inspections in recording and organizing all the information needed, pointing out critical aspects that need special attention;
- Assist the analysis of data from several inspections allowing to draw conclusions regarding construction history and typical damage and causes.

The tree-like organization of the TG1 form has been retained and enriched with a classification of types of structures and damage for each level (Fig. A1). The first part of the form deals with general information on the BUILDING, then each building can have one or more roofs (SYSTEMS), composed of a PRIMARY and a SECONDARY structure; each of these can be composed of UNITS (groups of elements repeated with the same arrangement), and of ELEMENTS and CONNECTIONS between elements.

Each part of the form has a first section on geometrical and typological aspects (Fig. A2), and a second section on damage. Structural types have been grouped into families according to their structural behaviour rather than their geometrical arrangement. Clearly, not all local variations have been considered. Past interventions (alterations, repairs, etc) can be recorded too. As highlighted by Parisi *et al.* (2013) the effect of past interventions is particularly critical to evaluate, as they can be localized or involve the whole structure, and differently affect the original behaviour/concept of the structure. Thus the form includes only a description and picture/drawing of past interventions, not their evaluation.

2.2.1 Building

General information on the building's name, location, property, protection status, use, interventions, references and geometrical aspects can be recorded in this section. X and Y coordinates and the geo-referencing system have been included in order to be able to plot the results. Values, rather than categories, have been used for seismic, snow and wind loads, and the protection status has been simplified to ‘UNESCO’, ‘National’ and ‘Regional’, to suit every country. Inspections can be linked to each building, specifying: the date, the inspector’s name, the parts of the building inspected. Foreseeing the development of forms for the inspection of other load-bearing systems (vertical, floors, foundations), the load bearing system inspected can be specified too.

2.2.2 Roof

The shape, construction period, roofing material, height, span(s), structure type of each roof can be recorded (Fig. A2). The roof structure can be composed of elements only (common rafter roofs, common rafter roofs with a ridge support, purlin roofs), or units too, in one direction (2D framing), and in 2 or more directions (3D framing). Other information include if the roof space is in use and if there are accessibility limitations, which can affect the possible interventions. The Eurocode 5 Service Class can be estimated.

2.2.3 Unit

Units have been divided into trusses and frames, as defined by Yeomans (1992, pp. 26-28). It is important to record if the original structural concept is different from the present behaviour: e.g. a unit might have been designed as a king-post truss but is actually behaving as a king-post frame, because of poor design, poor construction, etc. A series of data can be recorded if homogeneous in the whole unit: the timber dressing (rustic or civil, which affects the kind of intervention that can be done), the timber species (grouped in softwoods and hardwoods), the section shape (round, rectangular, rectangular with wanes, trapezoid), the timber treatment, carpentry marks, signs of reused timber.

2.2.4 Element

Elements have been classified as working in compression, in tension, in bending or shear, or a combination of the above (Fig. A1). The dating of the element can be specified, if different from the rest of the unit, as well as all the other information related to the timber dressing, treatment, section shape, etc. Strength affecting defects/natural features (knots, checks, etc) and material degradation (fungi attack, insect attack, metal corrosion) have been included in this part only, as they cannot be homogeneous for a whole unit or roof. Since most countries have regulations for Visual Strength Grading (VSG) of new timber but not for VSG of in-situ historic timber, it was decided to include only the natural defects that can significantly alter the structural behaviour or reduce the strength of an element: the position of the pith, the slope of grain, knots in the tensile area and horizontal deep checks which alter the section inertia. The type, extent and status of material degradation can be estimated.

2.2.5 Connections and Secondary Structure

The part on connections and secondary structure is organized in the same way, the only difference being the types of connections, bracing systems and damage (Fig. A1).

2.2.6 Damage

An important distinction has been made between damage effects and causes. During an assessment, we record the visible effects of damage and estimate their causes. The form guides the inspector in doing that: lists of damage effects (deformations, displacements, rotations, cracks, etc) are suggested for each level (system, unit, element, connection), and for each of the effects selected the damage status and role can be estimated. Tampone's work (1996; 2007) was very useful to build the damage taxonomy (Fig. A1), as well as the work of Task Group 3 of Working Group 1 of COST Action FP 1101 on traditional carpentry joints (Sobra *et al.*, 2015). Regarding the status, a damage can be 'active' or 'non-active', but it is not always possible to judge. Therefore, a simple 'intervened on' can be chosen, meaning that an intervention has been done to repair the damage but no evaluation on its effectiveness is given. Regarding the role, a structure is often affected by a sequence of damage rather than a single one, and it is important to identify the first one that caused all the others. This first one is defined as 'primary' damage, whilst all the others are defined as 'secondary' ones.

The causes of primary damage have been grouped in:

- Poor design (insufficient dimensions, inefficient joints, inefficient overall arrangement);
- Poor construction (poor material quality, poor seasoning, poor treatment, poor detailing, alterations of design);
- Material degradation (fungi attack, insect attack, metal corrosion);
- Poor maintenance;
- Interventions (increase of dead loads, repair/consolidations);
- Extreme actions (wind, fire, earthquake, snow, impact loads, settlements).

The specific type of causes vary in each part (roof, unit, element, connection) but the groups remain the same. The forms previously discussed (Frese and Blas, 2011; Toratti, 2011; Hansson, 2011) have helped in defining the possible causes of damage.

Poor design, poor construction, and all the other, can also be recorded as potential causes of damage, called 'unfavourable conditions'. This means they have not caused damage yet but might be a problem in the future, which is why they should be recorded nonetheless. Other unfavourable conditions have been included too, such as poor ventilation and the presence of bats/wasps/pigeons.

Whilst the geometrical/typological aspects remain the same, damage can change in time, and its evolution and development must be recorded. Thus the date of inspection has been included in the damage part.

2.3 Form

A main menu and linked forms have been created, to allow for an easier use and visualization of the form. Instructions have been included in the main menu, explaining how the form is organized and the nomenclature used.
Drop-down menus with fixed lists have been included to help users in both filling the data, as they give suggestions, and in analysing it afterwards, as data filled in as free text is always less homogeneous and less easily searchable (Fig. A2). Items can be added to the drop-down lists and more than one choice can be selected where appropriate. 'Other' and 'unknown' have been included as choices in every drop-down menu, to not force users in choosing something that does not match their judgment. The possibility of adding descriptions and pictures/sketches has also been provided.
The form is suitable for both quick and more thorough assessments. Some fields have been repeated (such as the timber dressing, the timber species, etc) at different levels, so that if they are homogeneous for the whole roof, or a whole unit, they do not need to be repeated for each element. Moreover, whilst providing space for all the information that one might want to record, all the fields have been left as 'non-required', so that they can be left blank: only the information that is available and useful for the specific purpose of that inspection should be recorded. Data can be changed and added any time later on.
There are many terminology issues, as types of roof structures, elements and connections have different names in different countries, and even the terminology associated to different damage/failures types is not always clear for English-as-a-second-language speakers. It was decided to solve this problem with drawings/sketches, which work as legends for the drop-down menus and other terms that might be misinterpreted (Fig. A2). Many terminology issues remain though: a work on terminology is a complex and long activity that was outside the scope of this work.

2.4 Future developments

The database model and form were presented and discussed at the COST Action FP 1101 meeting held in Trondheim, Norway, on 18th/19th June 2015, and at the COST Action FP 1101 final conference in Wroclaw, 8th September 2015. The feedback received was used to revise it. The form has been distributed amongst TG1 members for further revision and validation. There is also the possibility of it being implemented in an online version, in collaboration with a research group who has developed a semantic database model for the assessment and diagnosis of historic structures (Cacciotti *et al.*, 2015).
Future developments include extending the methodology to the development of forms for other load-bearing systems, incorporating data also from non-destructive/minor-destructive testing in order to quantify the damage in addition to characterizing it.
The data collected through the form could also be useful to associate each type of damage with the most suitable repair intervention (Harte *et al.*, 2015).

3 CONCLUSIONS

A database model and associated form for the assessment of historic timber roof structures has been developed based on the work of COST Action FP1101 and ADCRU at the University of Strathclyde. The aim is to guide visual inspection through a structured digital form, collecting a relevant amount of homogeneous data recording and reporting typical damage/vulnerabilities of structures. This is the basis for deriving vulnerability factors to predict failure mechanisms and identify urgent interventions. The development of this data collection and analysis procedure will support professional practice and increase knowledge on existing timber structures. Once validated, the approach used (the tree-like organization of the form, the flexibility for its use in both quick and in-depth inspections, the graphics explaining the relevant terminology, etc.) could be applied to develop forms for the analysis and assessment of other structural systems.

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Fig. A1: The tree-like organization of the form, with structural types and damage effects.

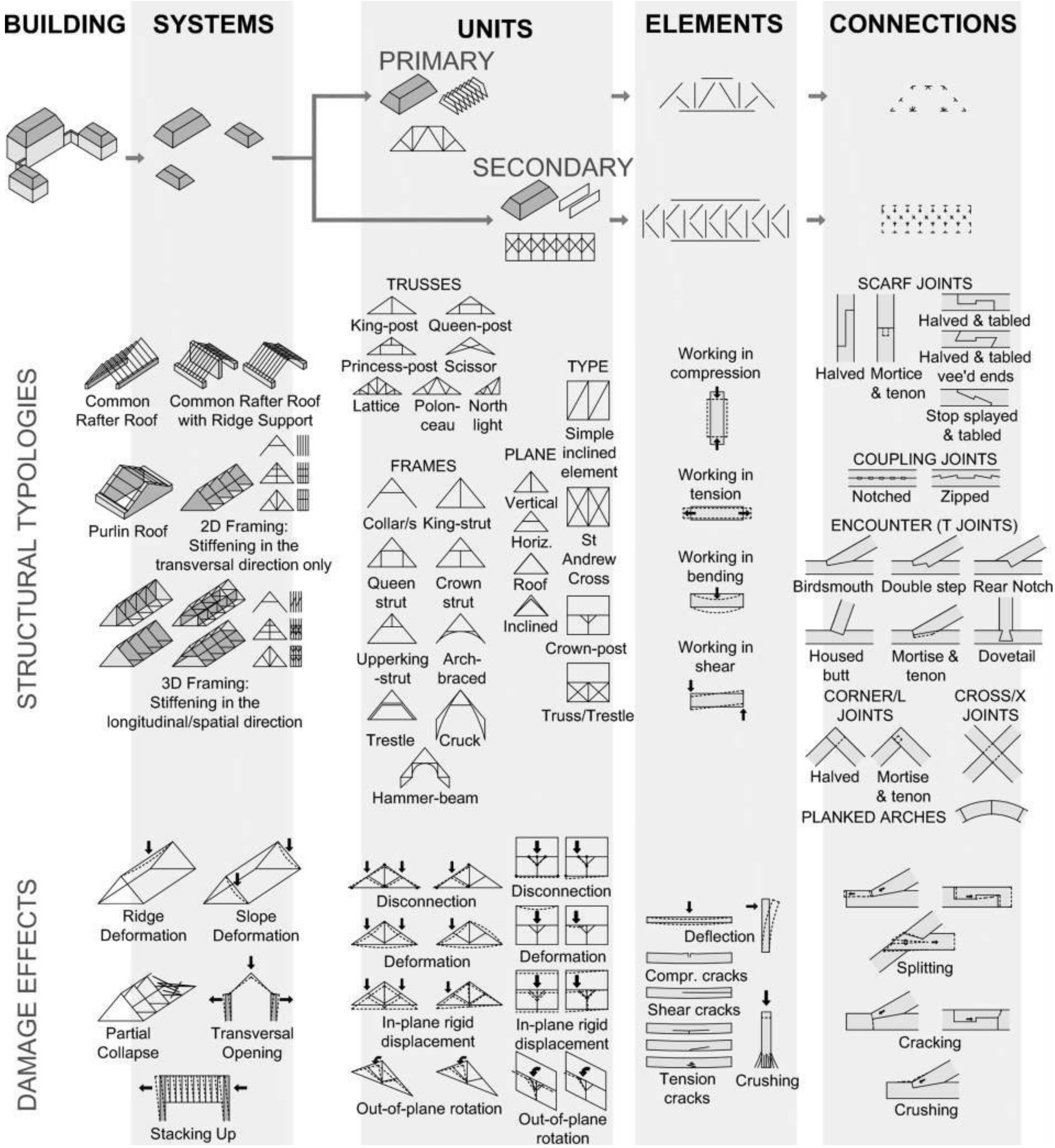
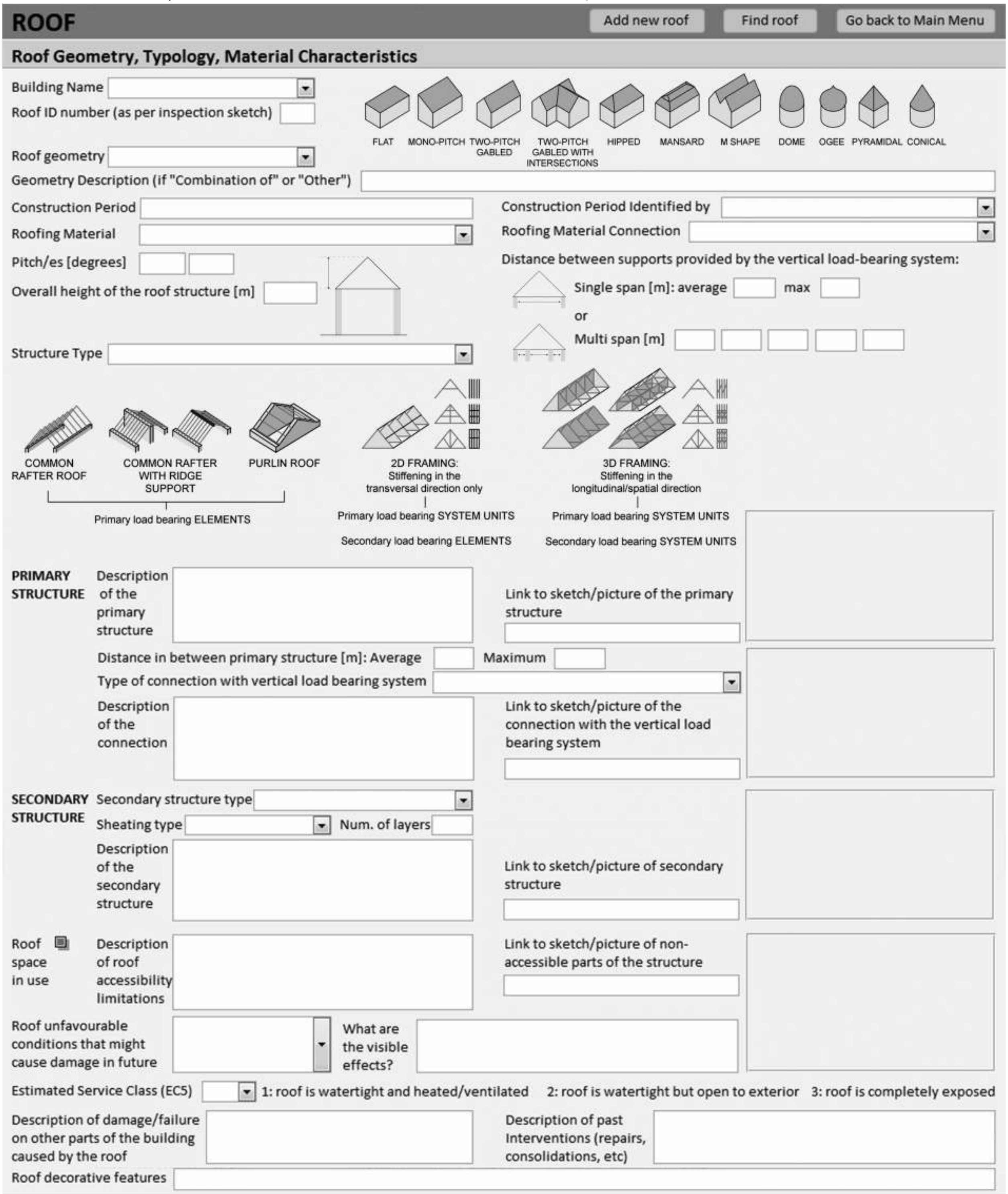


Fig. A2: Form screenshot (section related to roof geometry, typology and material characteristics) with list of terms included in the drop-down menus.



ROOF Add new roof | Find roof | Go back to Main Menu

Roof Geometry, Typology, Material Characteristics

Building Name

Roof ID number (as per inspection sketch)

FLAT, MONO-PITCH, TWO-PITCH GABLED, TWO-PITCH GABLED WITH INTERSECTIONS, HIPPED, MANSARD, M SHAPE, DOME, OGEE, PYRAMIDAL, CONICAL

Roof geometry

Geometry Description (if "Combination of" or "Other")

Construction Period

Construction Period Identified by

Roofing Material

Roofing Material Connection

Pitch/es [degrees]

Overall height of the roof structure [m]

Distance between supports provided by the vertical load-bearing system:

Single span [m]: average max

or

Multi span [m]

Structure Type

COMMON RAFTER ROOF, COMMON RAFTER WITH RIDGE SUPPORT, PURLIN ROOF — Primary load bearing ELEMENTS

2D FRAMING: Stiffening in the transversal direction only — Primary load bearing SYSTEM UNITS; Secondary load bearing ELEMENTS

3D FRAMING: Stiffening in the longitudinal/spatial direction — Primary load bearing SYSTEM UNITS; Secondary load bearing SYSTEM UNITS

PRIMARY STRUCTURE Description of the primary structure

Link to sketch/picture of the primary structure

Distance in between primary structure [m]: Average Maximum

Type of connection with vertical load bearing system

Description of the connection

Link to sketch/picture of the connection with the vertical load bearing system

SECONDARY STRUCTURE Secondary structure type

Sheating type Num. of layers

Description of the secondary structure

Link to sketch/picture of secondary structure

Roof space in use

Description of roof accessibility limitations

Link to sketch/picture of non-accessible parts of the structure

Roof unfavourable conditions that might cause damage in future

What are the visible effects?

Estimated Service Class (EC5) 1: roof is watertight and heated/ventilated 2: roof is watertight but open to exterior 3: roof is completely exposed

Description of damage/failure on other parts of the building caused by the roof

Description of past Interventions (repairs, consolidations, etc)

Roof decorative features

DROP-DOWN MENUS:

- Building Name: any building included in the ‘building form’ will appear in the list
- Roof Geometry: flat, mono-pitch, two-pitch gabled, two-pitch gabled with intersections, hipped, mansard, m shape, dome, ogee, pyramidal, conical, combination of, other (as in graphic legend)
- Construction period identified by: estimated, reported, dendrochronology
- Roofing material: slates, timber shingles, copper plates, lead plates, tiles, thatch, other, unknown
- Roofing material connection: timber pegs, metal nails, other, none, unknown
- Structure type: common rafter, common rafter with ridge support, purlins, 2D framing, 3D framing, other (as in graphic legend)
- Type of connection with vertical load bearing system: timber wall-plate, steel wall-plate, reinforced concrete wall-plate, reinforced masonry wall-plate, timber discontinuous, steel discontinuous, other, none, unknown
- Secondary structure type: sheating, purlins, common rafters, bracing, other
- Roof unfavorable conditions that might cause damage in future: poor design, poor construction, poor maintenance, poor ventilation, presence of pigeons/wasps/bats
- Estimated Service Class (EC5): 1, 2, 3