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CONNECTIONS TESTING AND RELIABILITY ASSESSMENT OF TIMBER CONNECTIONS WITH DOWEL-TYPE FASTENERS.

E. Moreno-Zapata[1], B. Iraola[2], R. Quinteros-Mayne[3], I. de Arteaga[4], P. Tanner[5], C. Lara[6], J.M. Cabrero[7]

ABSTRACT: The accurate description of the structural behaviour of structural timber connections is still an open issue, which poses many unresolved challenges. The REACT research project engages in developing a reliable framework for the design of structural timber connections. Based on an extensive experimental campaign and novel multi-scale models, it will provide a sound reliability assessment of timber connections. This knowledge will stem from a multilevel analysis, ranging from the material up to the connection level, with a special focus on the interaction of timber with dowel-type fasteners.

As a major contribution, the project will deliver information for design practice, allowing to make use of the obtained knowledge in a simple yet efficient way.

KEYWORDS: Timber structures, Structural connections, Experimental tests, FEM, Multi-scale modelling, Computational mechanics, MonteCarlo Analysis

1 INTRODUCTION

Although timber is one of the oldest construction materials known to man, the scientific knowledge about its material behaviour is often surprisingly poor. Due to its orthotropic material structure, growth irregularities, and hundreds of different species, wood, as a natural material, is one of the most complex building materials.

The required development of appropriate design rules for current tall buildings poses a challenge to satisfy the required design criteria (e.g., vibrations, creep, avoidance of brittle failure modes, robustness) [1]. Furthermore, many unresolved challenges hinder the designer from obtaining a realistic prediction of the actual performance and reliability of structural timber connections.

Though Finite Element Models are the main technique to simulate timber structural behaviour, the required material models for comprehensive modelling of timber response are not yet fully developed, and moreover, offer high accuracy at the expense of high computational costs. Many different approaches have been developed by several researchers [8,12-14,19,20,33,34]. Among others, the main challenging points in timber structures simulation are high variability in material properties, presence of random singularities such as knots, complex microscopical structure with fibres and layers, surface finish and influence on contact behaviour, different behaviour in tension and compression; different failure mechanisms (brittle and ductile) for different orientations and loadings.

There are strong economic and safety reasons for developing a reliability assessment of the design framework of structural timber connections, which explicitly takes into account the interaction between components, and predicts the associated failure mechanism [2].

The REACT project, *Towards a Reliable and Efficient Analysis of Connections in Timber: material and interaction testing, and numerical modelling*, financed by the Spanish Ministry of Science and Innovation, and conducted in collaboration between the Onesta Wood Chair at the University of Navarra and researchers from the Institute for Construction Science Eduardo Torroja, aims at providing a new insight into the response and modelling of structural timber connection with dowel type fasteners. The following sections describe the proposed multiscale approach, which is explained in Figure 1 as well.

2 PROJECT TOPICS

The research project has the following objectives:

- Provide a multi-scale understanding of timber connections, from the material (micro-level) to the connection level (macro-level), with a

[1,2,4,7] Department of Building Construction, Services and Structures, ONESTA Wood Chair, University of Navarra, Spain; [1] emorenoz@unav.es; [2] bisaenz@unav.es; [4] iarteaga@unav.es; [7] jcabrero@unav.es
[3] Facultad de Ingeniería, Pontificia Universidad Católica de Valparaíso, Chile; roberto.quinteros@pucv.cl
[5,6] Institute for Construction Science Eduardo Torroja (IETcc-CSIC), Spain; [5] tannerp@ietcc.csic.es; [6] carloslara@ietcc.csic.es

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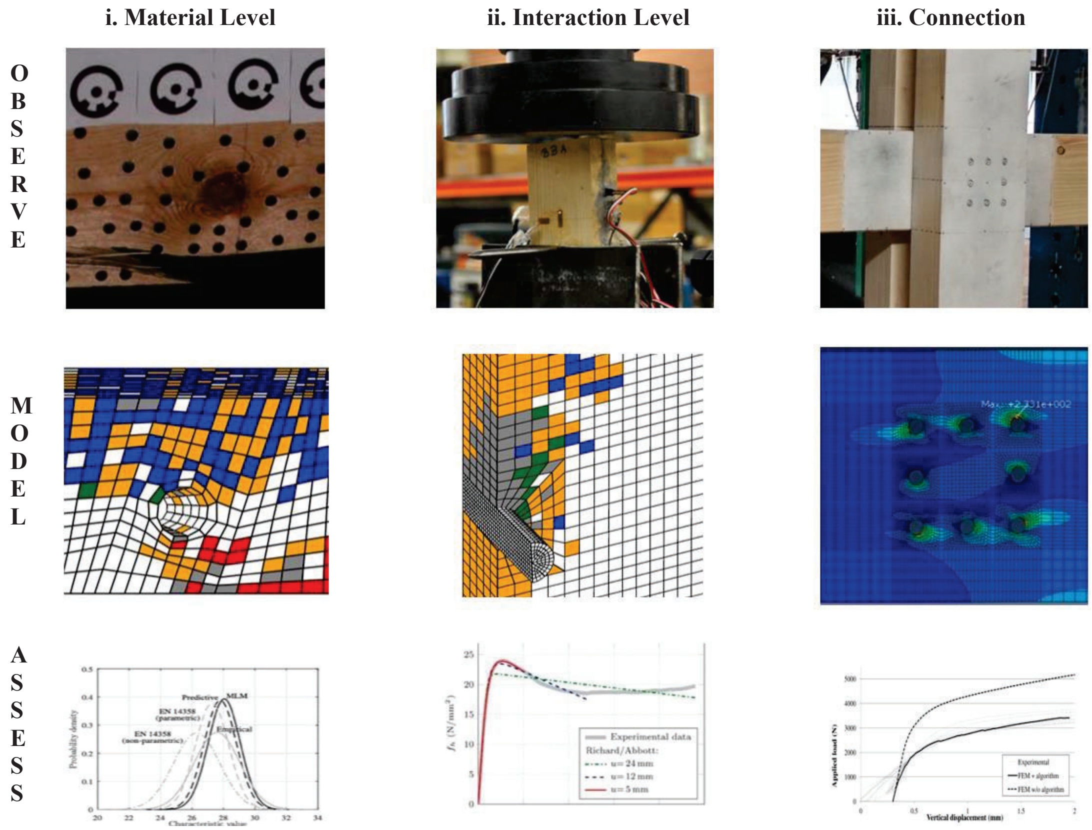

Figure 1: *Levels of analysis and related activities and results for each aim: tests, models and obtained results from the assessment. [10,17-20,31]*

particular focus on the interaction with the fasteners.

- Characterize more comprehensively the structural response of timber connections (stiffness, capacity and ductility) when submitted to realistic loads (i.e., different levels of interaction of forces, bending moment and shear and axial interaction…), with an emphasis of the capacity and type of failure.
- Develop three-dimensional models of structural timber connections based on a multi-scale modelling approach based on FEM, incorporating timber fracture.
- Assess the reliability of design models for timber connections.
- Deliver practical developments for the structural analysis and design of timber connections: verify and propose design models and criteria (i.e., overstrength) to ensure the ductile failure of the connection, an interaction criteria for the different types of loads and directions, an adequate design concept of the connection.

To accomplish these objectives, the project focuses on three different levels: material, interaction, and connection as a whole, and makes use of experimental tests, numerical finite elements modelling, and analytical models. The following sections describe the different topics.

2.1 OBSERVE THE BEHAVIOUR

A solid experimental foundation on which further theoretical and numerical developments can be built and validated is of course a preliminary and strong requirement. The experimental work plan is structured in the different levels to progressively apprehend the involved parameters and the complexity of the system. It is focus on products (solid wood and glulam) made of a representative species for softwood (spruce, Picea Abies), and two types of fasteners (dowels and self-taping screws). For each configuration, several replicates are testing to get statistically relevant distributions and properties. Such detailed results will be later used for different aims within the project, i.e., to validate the models for each level in detail, to provide material properties and their statistical distribution.

Additionally, to the traditional parallel and perpendicular loading testing, testing in intermediate angles (off-axis tests) are performed. Since parallel and perpendicular failure modes are different (i.e., plug-shear failure for the parallel tension loading and splitting for the perpendicular tension), the interaction at different angles and different connectors configurations needs to be studied. Figure 2 shows a depiction of the type connections to be tested. The

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project challenges the current test setups by developing a new test philosophy, based on the available DIC techniques [21, 22] and off-axis tests to get new knowledge into timber response.

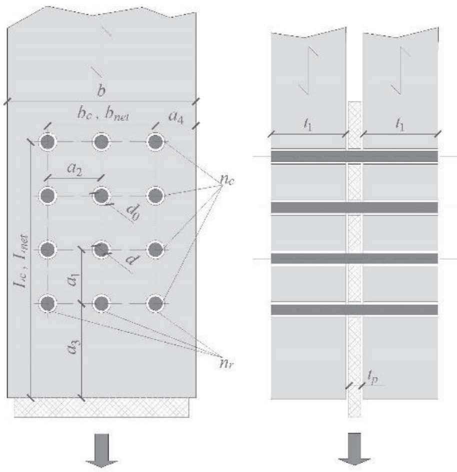

Figure 2: *Representative depiction of the types of connections to be tested with slotted-in-plates and dowel-type fasteners [9]: front (left) and side (right) views.*

2.1.1 Material tests

The experimental campaign at this comprehension level focuses on the mechanical response of timber. Samples with different anatomical features (with defects, i.e., knots, finger-joints) are tested instead of the classical approach of testing clear wood specimens (with no defects).

Material properties will be obtained using the current standard procedures [23], and by a novel experimental procedure, based on off-axis tests (as those depicted in Figure 3) and the use of DIC techniques [21,22]. The tests will provide the characterization of the different required material parameters (classical tests provide strength parameters and not actual material properties [3]), their variance, and correlation, as required for the reliability analysis. Non-destructive techniques (i.e., ultrasound) will be additionally used at each piece, to have an additional source of information, and a way to assess how to indirectly obtain material properties.

This level will give us a comprehensive description of the behaviour of the material, its fracture behaviour, the coupling among the different material orientations, their statistical properties, as well as the influence of the different anatomical defects.

2.1.2 Interaction test

This level will deal with the interaction of timber with a single dowel-type fastener, conceived as a system property [24]. Existing test standards will be again challenged. Two main configuration types, at different load and fastener angles to the grain, related to the distinct roles of the fasteners are developed: load transfer through contact between fasteners and timber by the standard [25] and novel off-axis [26] embedment tests; and the application of reinforcement by performing off-axis tests of reinforced timber. The versatility of the novel approach and the detailed description obtained employing the DIC will provide an improved understanding of the occurring phenomena.

The following phenomena are expected to be understood in more detail: rope effect, friction, clamping, residual stress around the fastener, the influence of load-to-grain angle, predrilling, and possible execution tolerances. The different required properties of the fasteners (i.e., withdrawal strength, head pull-through capacity) will be tested employing standard procedures [25,27-32].

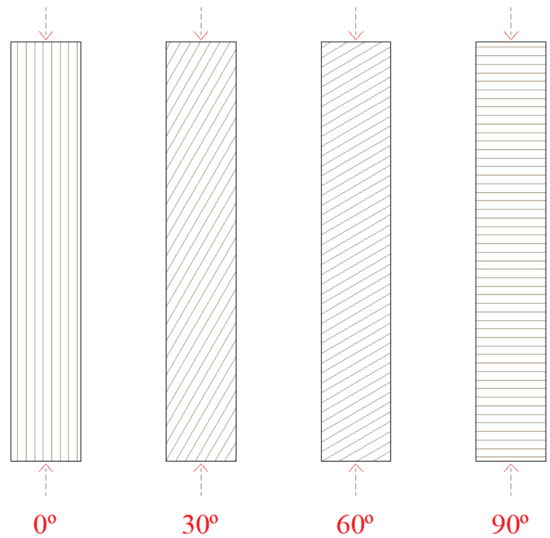

Figure 3: *Off-axis tests for the material level. Depicted, the concept for compression tests.*

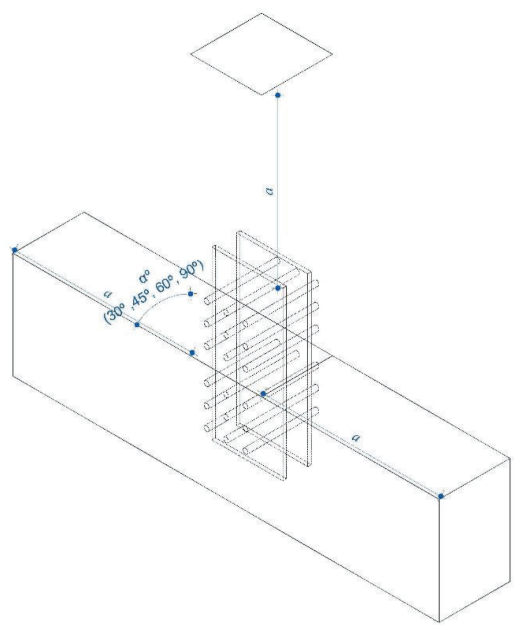

Figure 4: *Main concept and scheme for the tests of the structural connections, with a varying angle between members.*

This study will give us a new comprehension of the complexity of the stress field around dowel-type fasteners, the resulting stress field, and the related failure process.

2.1.3 Connection tests

Reinforced and unreinforced connections with different geometrical parameters and load orientation will be tested. While most available experimental studies focus on parallel tension loading [31,32], we will pursue load application setups to achieve complex and realistic load patterns, in which bending, shear, and axial interaction are present, to provide an understanding of the existing interaction, related to those observed in the previous levels. Figure 4 shows a depiction of the proposed test specimens.

A detailed description of the actual geometry after assembling the specimen will be obtained, which will provide a reliable source to quantify the execution defects before testing (i.e., misalignment, straightness of fasteners, actual positioning). These measurements will provide a database for its additional use for the uncertainty of execution in the reliability analysis.

The actual material properties of both timber and fasteners employed in the connections tests will be obtained after the tests, to reduce the uncertainties in the performed tests. To that purpose, pieces of the undamaged material will be extracted after testing and will be performed the corresponding material tests.

This study will give us a new perspective on the behaviour of connections. Based on the previous levels, which provide the influence of anatomical features and the interaction with the fasteners, here an understanding of the interaction of these different mechanisms altogether and their influence on the global response will be reached.

2.2 MODEL THE RESPONSE

This topic will develop an efficient FEM modelling framework of the connection, aiming at two different types of Finite Element Models. Within this work package, first, a usual (in research practice) three-dimensional FEM models for comprehensive modelling of the full response of the connections will be developed. ABAQUS will be used as the main platform [11,16,18,19], which will serve as the basis of the developments within this aim.

Subroutines for the material and the interaction levels within the FEM platform will be developed in two iterative steps: the first-generation models will serve as a validation of the techniques applied at each level and will be based on usual 3D models with solid (hexahedral) elements, in which the material and interaction levels will be implemented within user-defined routines into the commercial FEM code Abaqus via the different available interfaces, i.e. UMAT, UINT.

However, these 3D models are cost-intensive, not appropriate for practice. Carrying out reliability analysis based on them would be unfeasible. Therefore, to reduce the computational time, second-generation multi-scale models will be developed. These models, though simple, will be able to incorporate the material fracture, so they provide comprehensive modelling of the behaviour of timber connections at a reduced computational cost. These models will be used for the development of the required dataset for the subsequent reliability analysis. To that extent, realistic properties, mostly based on the obtained dataset from the experimental set and analysed in the following Aim, will be fed into the model. Moreover, these models, may provide a simple and reliable way to model connections in future practice.

To obtain the interaction and linking between the different models and ABAQUS, and the required parameterization for the stochastic models, a framework with the additional use of MatLab, Python, and C++ will be developed.

2.2.1 Material model

The main focus of this level is the modelling of the timber failure response, defined by the onset of failure, based on appropriate failure criteria for timber [33,34], and the following behaviour, either ductile or brittle, for the different stress combinations, and the different anatomical features.

Three-dimensional models reproducing the tests at this level consisting of simple geometries will be used to validate the developed material model. It will allow to develop appropriate modelling techniques for the material, and to incorporate in a realistic way timber defects, such as knots and grain deviation.

An appropriate homogenization technique will be developed, i.e., by adequate mixture rules to assign anatomical features and their corresponding properties to each element or representative volume element [15] to derive a product model for its use at higher levels. The developed script will provide realistic modelling of the material behaviour of timber products.

2.2.2 Interaction model

This level aims at developing an efficient technique for the modelling of load transfer through direct contact and reinforcement by embedment of fasteners into the timber. This model's developments will already take advantage of the previous material model since it is needed to reproduce the timber response. These models will be validated against the experimental tests.

2.2.3 Connection model

In the FEM it is crucial to appropriately define the coupling conditions for the different components. A full and detailed description of the connections' response (i.e., full non-linear load-slip behaviour, ultimate displacement, failure type…), and the resulting stress fields and interactions among the constitutive components will be obtained. These models will be validated against the existing tests.

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2.2.4 Multiscale model

A multiscale model will be developed based on previous achievements. The proposal will be based on previous developments. Mainly based on the Beam on Elastic Foundation [8,37-39]. Such models, which make use of connector, beam and shell elements, reduce the computational cost to a fraction (results in the order of minutes), in comparison to the 3D models used in the previous parts. The multiscale model will incorporate fracture behaviour of timber, allowing for the first time for a full multiscale model of timber connections incorporating all the required parameters.

2.3 ASSESS THE RELIABILITY

This topic will develop a framework for the reliability assessment of timber connections, based on the dataset derived from the previously developed multiscale FEM models and the connection tests. The performed analyses will include material, execution, and geometric parameters as stochastic variables, based on the probabilistic properties derived in Section 2.1 and databases from the literature [40]. The developed framework in Section 2.2 will serve to calibrate existing and newly proposed design models to achieve the required level of calibration required for the relevant design situations. For this purpose, the uncertainties associated with such models must be quantified, which constitutes a crucial step to provide safe and efficient use of timber structures.

Load carrying capacity models should be calibrated to achieve the level of reliability required for the relevant design situations. For this purpose, the uncertainties associated with such models must be quantified, which is typically done by adjusting the model based on a best-fit criterion and by comparing the model outcome to the results of measurements and experimental tests. The degree of uncertainty of the model may be described in terms of the bias and the coefficient of variation that result from such comparisons. Additional conditions, such as measurement errors and statistical uncertainties due to a limited data set, real structure-specific conditions and scale effects should also be taken into account if required. Moreover, uncertainties describing random effects that are neglected in a resistance model and simplifications in the mathematical relationships on which it is based should be additionally incorporated.

For the calculation of the design value of the resistance, the Eurocode [41] makes a distinction between a partial factor associated with the uncertainty of the resistance model, γ_{Rd}, and a partial factor for material properties, γ_m. Depending on the type of structure considered, the partial factor γ_{Rd} may cover uncertainties in the resistance model; the bias in the resistance model, when relevant; and geometric deviations, if these are not modelled explicitly.

For certain types of structure, γ_{Rd} and γ_m may be combined into a single partial material factor, γ_M, and applied to material properties. Similarly, when applying partial factors to resistance for certain types of structure, γ_{Rd} and γ_m may be combined into a single partial resistance factor, γ_R.

The statistical determination and calibration of resistance models based on tests must consider the statistical uncertainty due to a limited number of results. To overcome such problems, the research project will involve the use of numerical models to complement the available test results. The model uncertainty should be treated as a random variable, and this research proposal will do so. In this context, it should be noted that if advanced models are used to calibrate simplified engineering models, then model and statistical uncertainties are present on both levels and should be taken into account simultaneously.

2.3.1 Dataset description

A detailed analysis of the test results from the experimental tests (see Section 2.1) will be performed, adequate for the assessment procedure to obtain the adequate statistical description, and analysis of the obtained results, assuming the appropriate distribution function for its uncertainty and variability. Probabilistic models for uncertain resistance characteristics may in principle be formulated at any level of approximation within the range of a purely scientific mathematical description of the physical phenomena governing the problem at hand (micro-level) and a purely empirical description based on observations and tests (macro-level).

In engineering analysis, the physical modelling is, however, normally performed at an intermediate level sometimes referred to as the meso-level. Reliability analysis will, therefore, in general, be based on a physical understanding of the problem but due to various simplifications and approximations, it will always to some extent be empirical. This essentially means that if experimental results are compared to predictions obtained through physical modelling, omitting some effect, then there will be a lack of fit. The lack of fit introduces a so-called model of uncertainty, which is associated with the level of approximation applied in the physical formulation of the problem.

It is important that the model uncertainty is fully appreciated and taken into account in the uncertainty modelling. This will be done in the project, following the principles established in the JCSS Probabilistic Model Code [40].

2.3.2 Montecarlo analysis

A Montecarlo analysis will be developed at the connections' level, including stochastic variables with values derived from the measurements within the experimental campaign. It is envisaged to also include the execution tolerances, taken from existing execution standards. The developed framework will provide a detailed insight into the response and reliability of timber connections, which is needed in current practice. It will provide an answer into problems such as overstrength, ductility, and type of failure, by giving special attention to estimating the proportion of different connection failure types within the considered design.

2.3.3 Model's uncertainty

This aim focuses on assessing the model uncertainty. The assessment of this variable is based on a comparison of model and test results and the determination of the associated partial factors include the following steps:

- Compilation of available test results.
- Calculation of the resistance for each of the tested specimens by using resistance models for relevant failure modes and measured values for dimensions and material properties.
- Determination of the theoretical load-bearing capacity and the associated failure mode.
- Comparison with experimental failure mode and capacity.
- Statistical evaluation of the results, in which the theoretical and the observed failure mode match.
- Suitable probabilistic description of the model uncertainty (lognormal distribution is commonly an appropriate distribution function).
- Determination of resistance model uncertainty partial factors depending on the partial factor format, parameters of the model uncertainty variable, target reliability and sensitivity factor.

When generalizing the model uncertainty beyond the scope of the database, trends with regard to mean and scatter should be carefully considered.

2.4 APPLY IN PRACTICE

Scientific knowledge, such as the herein proposed, must be made available for practice. Therefore, as a final step, all the developed scientific knowledge and strategies will be incorporated into tools for practice: design models for their consideration in design codes, such as the Eurocode.

Reports will be circulated and presented at the relevant Working Groups and Committees within the European standardization framework.

Such resistance design models are usually based on a combination of mechanical principles and empirical relationships. Newly developed models for inclusion in structural design codes should preferably be based on mechanical principles and meet the required level of reliability.

The expected outcome of the research plan will moreover allow developing improved design models for the capacity of the connections. It is expected to develop design models for the brittle failure of connections in the parallel and perpendicular direction and provide an interaction rule among these two capacities. The calibration procedure within Section 2.3 will allow providing a sound and consistent reliability background to the used fitting and safety coefficients in those models.

2.4.1 Design model

Based on the deep gained understanding of the behaviour of timber connections and their components, a design model will be developed to improve those existing (or still non-existing) within design codes. These models will be based on the existing design models from the literature (i.e., EYM) for the capacity of timber connections, for both failure types, ductile (EYM) and brittle, and will be calibrated, as described in Section 2.3. Additionally, it is expected to deliver a sound model for the brittle failure of timber connections for different load types and interactions. The developed design models will provide design principles and application rules for the design of timber connections in the future generations of timber design standards.

2.4.2 Reliability parameters

The statistical description of the uncertainty and the proposal of the developed reliability framework, which may be derived based on the JCSS Probabilistic Model Code [40], will be developed and presented at the appropriate standardization committees. The developed reliability assessment will allow proposing adequate safety concepts and calibration parameters for the design of timber structures and connections.

3 CONCLUSIONS

Tall timber buildings are becoming increasingly popular while challenging our surprisingly poor scientific knowledge of timber structures. However, current design approaches are still based on experience and tradition, and they are neither efficient nor reliable: while most members in timber structures are around 40-60% over-designed due to connection requirements [4,5], almost 25% of recent collapses of timber structures were related to connections. [2,6,7]

REACT engages in developing a reliable framework for the design of structural timber connections and structures. Based on the described extensive experimental campaign and the developed finite element models, both 3D-based and the novel multi-scale models, it will provide a sound reliability assessment of timber connections. This knowledge will stem from the described multilevel analysis, ranging from the material up to the connection level, with a special focus on the interaction of timber with dowel-type fasteners.

The experimental campaign focuses on three observation levels: material, timber-fastener interaction, based on standard and novel techniques; and connections. In this latter, the focus will be on realistic load patterns, in which bending, shear, and axial are present, to provide an understanding of the existing interaction among them. This challenges the current knowledge, mostly based on simple loading schemes.

This level-based experimental knowledge will inform the development of a multi-scale numerical model for timber connections which will be used to carry out the required stochastic models for the MonteCarlo Simulation and the subsequent reliability analysis of structural timber connections.

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As a major contribution, the project will deliver information for design practice, allowing to make use of the obtained knowledge in a simple yet efficient way.

To exploit its extraordinary ecological potential and to enable its structural use, improved comprehension of the structural response of timber connections is required. REACT can make a significant difference towards more efficient, reliable, and safe timber constructions.

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