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Diagnosis and monitoring of timber buildings of cultural heritage

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Abstract

The aim of this paper is to present a methodology for the evaluation of historical timber frame structures, based on numerical modelling coupled with on site measurements. The underlying question which is raised in this research project is: how can we assess the current state of safety of a structure which has several centuries of existence, and is likely to undergo new loads for various reasons? The dynamic response of a timber frame bell tower to the swinging bell action has been measured at critical points, identified by a parametric study, and compared to a FE analysis of the system, using modified EC5 assumptions. The results have shown that the kinematics of horizontal displacements is correctly described by the numerical model, as well as the calculated amplitude of movements.

Keywords: Old timber structures; Dynamic analysis; Experimental design; Finite element model

1. Introduction

Preservation of the architectural heritage is considered as an important issue in modern societies: in addition to their historical and epistemological interest, cultural heritage buildings significantly contribute to the economy in a context where tourism and leisure become major industries; preserving historical constructions is finally not only a cultural requirement but also an economical and developmental demand.

The study of historical constructions must be undertaken through modern technologies and knowledge; modern requirements for an intervention include reversibility, non intrusiveness, minimum repair, respect of the original, as well as the functionality and structural stability.

In this paper, an old (over four centuries) timber frame construction is considered. The aim of the research is to present a general method for the evaluation of such a structure, considering the fact that its geometry is complex and that material properties are unknown and cannot directly be assessed experimentally. An estimation of these properties, especially for joints, can be made using modified EC5 assumptions. A FE modelling coupled with on site dynamic testing of the structure has been used to calibrate the most important parameters with regards to the structural behaviour. Statistical analysis can then be used as a decision tool for model updating.

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This work is part of a general project (TOOL2TIM) on the safety assessment, monitoring and repair of timber structures.

2. Numerical tools for load bearing timber structures

The reliability of a timber structure has to be estimated for maintenance, repair or structural modification. An obvious mean is to conform to building standards that fulfil the safety requirements (usual building, standard timber and materials ...); in that case, only simple trivial canonical modelling is used, because of design costs. Different types of uncertainties, such as physical, statistical and modelling, must be taken into account. For many other cases (old timber frames, complex structures with high 3D effects, unusual climatic environment, mechanically complex joints, non standard material), standards and simple modelling cannot be applied. Moreover, if a reliability analysis has to be checked for non canonical structures, the limit state equation must be based on response surface methods rather than analytical formulations [1,2] using simplified but accurate modelling: very few values are however available. For these reasons and for smart follow up of a frame, an appropriate and sophisticated mechanical modelling has to be undertaken. The more sophisticated is the modelling, the more important is the number of parameters and their degree of uncertainty.

Different steps have to be followed in order to reduce the modelling and some physical uncertainties of timber structures:

1. The first step is the geometrical assessment of the model. For structures with high creep deformation or out-of-plane evolution (often seen in buildings of cultural heritage), laser or optical techniques can be carried out: numerical methods have to be applied to assess the mechanical discretisation and take into account the effects of non straight beams or non canonical joints.
2. Then, optimisation techniques have to be performed in order to test the weight of each parameter or sets of parameters on the structural response (displacement, stresses, modal frequency...). Among these methods, numerical designs of experiments have been successfully applied on middle size wooden bell towers [3–5]. However, the method has shown its limits as the problem size is growing to larger structures.
3. As the set of mechanical parameters is reduced, their identification has to be done according to their weight. Numerical methods are used to define on site measurements and to calibrate the mechanical values of the model.
4. Probabilistic analysis is required to account for modelling uncertainties and to update model parameters.

On site measurements are hard to carry out because of the lack of Non Destructive Evaluation (NDE) tools and the loading of the frame. If identification by conventional static loading can be performed by Genetic Algorithms, research is aiming dynamic analysis of natural loading: wind and service vibrations. Modal identification and follow up require sophisticated numerical methods. Some applications of NDE techniques on historical timber constructions can be found in e.g. [6–8].

The following work presents an application of some mentioned tools on an old timber frame system. The case study is a bell tower (one of the belfries of the Metz cathedral in France) supporting a 10.5 tons bell acting as a dynamic oscillator on the structure. The bell has not been ringing since almost a century because of masonry falling stones, but a visual inspection does not reveal any element of potential pathology.

3. The bell tower application

3.1. Geometrical assessment and finite element analysis

The first step of the experimental study has been to collect information in order to create the 3D finite element model of the wooden belfry and its bell with Autocad® and Abaqus® software. The belfry is submitted to two different kinds of loads: a static load (gravity), and dynamic loads due to the swinging bells. In order to estimate the loads induced by the swinging bell, we realized a 3D model of the bell. We thus obtained the mass $M = 10{,}372$ kg of the bourdon bell, the distance $L = 1.09$ m of the centre of gravity G to the rotation axis Z