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Numerical Modelling of a Wood Pavement of a 13th Century Building

Patrícia C. Raposo[a,b,*], Michael Andrade[c], José A.F.O. Correia[a,b], Maria E. Salavessa[c], Cristina Reis[a,b,c], Carlos Oliveira[a,d], Abílio de Jesus[a,b]

[a]*INEGI, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*
[b]*Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*
[c]*University of Trás-os-Montes e Alto Douro, apartado 1013 Quinta de Prados 5001-801 Vila Real*
[d]*Polytechnic Institute of Viana do Castelo, Atlantic Avenue 4900-348 Viana do Castelo, Portugal*

Abstract

The present work is based on a numerical study of a wood pavement of a Pousada medieval da Gralheira in Vila Real, Portugal, which is an example of the constructed patrimony of Trás-os-Montes. The negligence in the preservation of historic buildings lead to the current advanced state of deterioration, which implies a complex rehabilitation process. The features obtained in a visual inspection of the building and experimental campaign in wood specimens, made it possible to develop and calibrate a numerical model of the wood floor between the ground and first floors, of the Inn, to analyze the behavior of the structure in terms of serviceability limit state, so with a numerical model, one can predict the real behavior of the structure. The numerical models are powerful tools to aid in the structural design.

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Keywords: Numerical modelling; Wood structures; Historic buildings; Masonry structures.

1. Introduction

The built heritage is a physical testimony of the history of old city centers [1]. There is been an effort, in the last years,

* Corresponding author. Tel.: +351 225082151; fax: +351 229537352.
E-mail address: praposo@inegi.up.pt

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to preserve the historic buildings, and prolong their life [2]. It is difficult to obtain an analytical solution for woods, due to its nonlinear behaviour. Recurring to the use of numerical models based in finite element method (FEM) simulation is possible to overcome this impasse. With those numerical models is possible to make static and dynamic analysis. For the dynamic analysis are necessary more wood characteristics than the ones necessary to perform a static analysis, such as, inertia and damping forces. A good structural response model requires the creation of good material's behaviour models [3, 4]. Due to the high heterogeneity of wood is very difficult to obtain the strength, modulus of elasticity, etc. because it varies from specimen to specimen due to its irregularities, fibers orientation, etc. If the tested woods have irregularities the mechanical properties values should be of statistical nature [5]. A viable numerical model, which produces viable numerical simulations requires constitutive models that includes the irregularities in the behaviour of wood. The applicability of analytical models is limited due to the anisotropic behaviour of wood [6], leading to the use and development of the finite element model of the wood structure of the floor between the ground and first floors, presented in this work. By comparing the model with the displacement and deflection measured *in situ*, is possible to assess the viability of the model. This kind of models is important to assess the impact of the wood structures in the overall masonry structure, and to assess and take preventive measures of intervention, helping to develop an economic and adequate rehabilitation [7].

Nomenclature

$S_{Gk,j}$	characteristic value of permanent actions, $S_{Qk,1}$ the characteristic value of one of the variable actions
$Q_{k,i}$	characteristic values of other varying actions
Ψ_1	Ψ_i coefficient (RSA) [8]
$G_{k,j}$	characteristic value of the permanent action
$Q_{k,1}$	characteristic value of one of the variable actions
u_{fin}	final deformation
u_{ins}	instantaneous deformation
k_{def}	factor that considers the deformation increase over time as a consequence of the combined effect of fluency and water content
A-A	supported-suported
A-E(50)	supported-50% of embedding

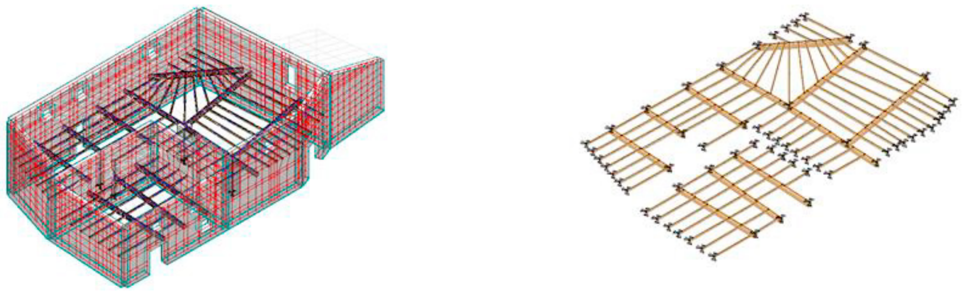
2. Numerical modeling

There is a high number of uncertainties associated with the materials that compose the historic structures so is necessary to adopt simplifications, in the materialization of structural models, through numeric models, which describes the behavior of the structures in an approximate way, allowing to verify the security of the structures, in this case of the wood floor structure [9]. With the numerical model of the floor is possible to predict the linear behavior of the wood until rupture. With the calibration of the model with the mechanical characteristics of the wood is possible to carry out a safety assessment. It is fundamental to consider in these models the structural scheme, material mechanical characteristics and actions applied in the structure [9].

2.1. Structural calculation model

A wood pavement structure numerical model was created using the *Arktec Tricalc 8.0* software in order to obtain its behaviour (loads, moments, displacements). Since the structural beams didn't have a regular diameter, was used their average value in the construction of the model. To represent the walls and pavement were placed distributed loads on the beams superior face. The obtained model is presented in Fig. 1. With aims to obtain a reliable model is necessary to do a calibration, by using the mechanical wood parameters obtained in experimental tests, but mainly due to vibration frequencies comparison of the model and the structure itself [10].

Despite the fact that the numerical models are a great tool to engineers, in design functions, is necessary that the model is correctly validated by comparing the model geometry, stresses and/or deformations with the expected values. The model adopted considered a hinged structure, simply supported on the wall, with physical and mechanical properties taken from EN348 (D30) standard [11], considering the minimum resistance class, D30, defined by visual inspection and experimental laboratory campaign, in order to obtain values next to real behaviour of the structure. Was considered a density of 530 kg/m^3 and an elastic modulus of 10 GPa [11]. The self-weight of the structure was obtained automatically by the program, and the load actions were obtained manually. The floor load used, considering the density of the wood, already defined, and a floor 2 cm thick, was 0.07 kN/m^2, the divisions load used was 1.0 kN/m^2 and utilization overload of 2.0 kN/m^2. Next step was to define the combination of actions, to check the Ultimate Limit State (ULS) was followed the equation (1) and for the use limit states, the equation (2), taking into account the rare actions, quasi-permanent and permanent combinations.



(a) (b)

Fig. 1. Numerical model of the wood pavement (images from: [9]).

$$S_d = \sum_{i=1}^{m} \gamma_{g,i} S_{G,ik} + \gamma_q \left[S_{Q,1k} + \sum_{j=2}^{n} \psi_{0,j} S_{Q,jk} \right] \quad (1)$$

$$S_d = \sum_{j=1}^{m} G_{k,j} + Q_{k,1} + \sum_{i=2}^{n} \psi_{1,i} \times Q_{k,i} \quad (2)$$

2.2. Validation of the numerical model

The *in situ* values were obtained by measuring it with a measuring-tape in a visual inspection to the building, obtaining a value of 2.0 cm. Fig. 2 shows the deformation of the beam, under greater deformation, according to the numerical model.

Fig. 3 presents the global displacements model for the ultimate limit state combination, showing the zones under higher deformation (red and orange). The numerical model is an important tool because can display the critical zones, and knowing which is the more critical beam it can be carried out a more detailed model to obtain the final deformation [12]. Equation (3) allows to obtain the final deformation, which is obtained for the rare action combination [13].

$$u_{fin} = u_{ins}(1 + k_{def}) \quad (3)$$

Table 1 presents the values of k_{def} that should be used and Table 2 shows the obtained values of deformation and the maximum permissible deflection according to Eurocode 5 [13]. By analysing the last table, it can be seen that the maximum value recommended was exceeded and was about 3.24 times higher than the value obtained *in situ*. These differences may be due to the fact that the numerical model considered the connection between the floor beams and the walls hinged, i.e. simple supported, which isn't according to the reality, due to the fact that the beams had a delivery in the walls, preventing them to turn easily as it can be seen in Fig. 4. Also the floor isn't in reality a superficial load, because it gives rigidity to the floor structure, behaving like a diaphragm, leading to smaller deformations.

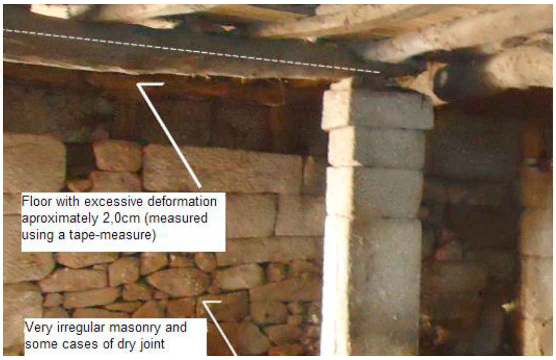


Fig. 2. Deformation of the beam under analysis (image adapted from: [9]).

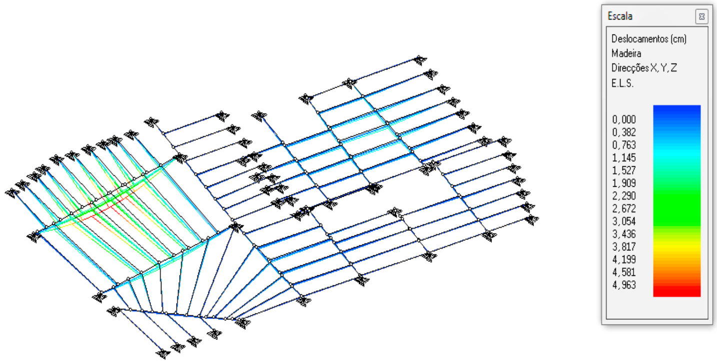


Fig. 3. Model of the global displacement of the floor structure (image from: [9]).

Table 1. K_{def} values for solid wood (Adapted from Eurocode 5: [13]).

Material	Standard	Service class 1	Service class 2	Service class 3
Massive wood	EN 14081-1 (2005)	0.60	0.80	2.00

Table 2. Rare combination of shares by applying the coefficients K_{def} (adapted from: [9]).

Rare actions combination, applying the K_{def} coefficients							
Permanent	Overload	ψ_2	K_{def}	$U_{fin,G}$ (cm)	$U_{fin,Q}$ (cm)	U_{fin} (cm)	f_{max}=L/200 (cm)
1.907	3.056	0.2	0.6	3.051	3.423	6.474	3.125

Fig. 4. Delivery of the wooden beam on the masonry wall (image adapted from: [9]).

In order to consider the embedment of the beams in the walls was created a model with a degree of embedding of 50% in one extremity and simple supported in the other, since the beams rested in a masonry column as showed in Fig. 2. In Fig. 5 is presented the deformation results for this new model, for ULS, obtaining a maximum deformation of 2.072 cm. Considering the rare actions combination, the results obtained with this new support conditions are presented in Table 3, and compared with the previous results for the simple supported beam. Placing a 50% degree of embedment in one extremity it's was obtained a numerical deformation only 1.35 times higher than the real deformation.

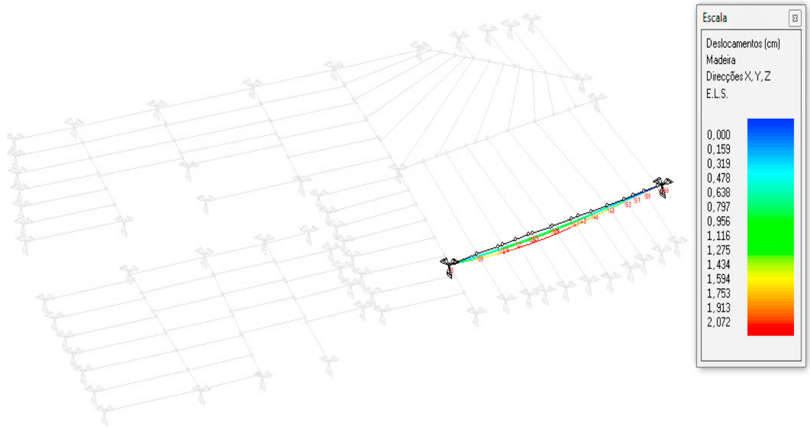


Fig. 5. Model of the most deformed beam of the floor structure (image from: [9]).

Table 3. Comparison between final deformation, for the two types of support conditions considered (adapted from: [9]).

	Rare actions combination, applying the K_{def} coefficient							
Support	Permanent	Overload	ψ_2	K_{def}	$U_{fin,G}$	$U_{fin,Q}$	U_{fin}	f_{max}=L/200 (cm)
A-A	1.907	3.056	0.2	0.6	3.051	3.423	6.474	3.125
A-E (50%)	0.796	1.276	0.2	0.6	1.274	1.429	2.703	3.125

3. Conclusions

The case-study building, from the 13th century, represents a rehabilitation challenge due to material's antiquity, heterogeneity, and lack of maintenance of the structure. Visual inspections can help to assess the existing pathologies and identify the major problems in the building. Also it is possible to calibrate numerical models with visual inspections made to the structure under modelling. The importance of the numerical models is that they provide a tool that allows the designers to understand the structural behaviour to be expected from the structure, and the necessities of reinforcement that they have, as the most loaded elements. In this study the numerical model considering the beams that support the floor, simple supported and 50% embedded was found to be a reliable model to predict the structural behaviour of the wood elements giving a deformation only 1.35 times higher than the real one. If in this model the floor was considered as a diaphragm and not as a distributed load the results should be even more accurate with the reality. The different values also are due to the difficulty associated with the correct representation of the structural elements geometry, since they have variable sections and different support conditions.

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