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PHENOMENOLOGICAL MODEL FOR SEISMIC DESIGN OF MULTI-STOREY CLT BUILDINGS: CALIBRATION OF INPUT PARAMETERS

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ABSTRACT: A numerical modelling approach for the prediction of the seismic response of multi-storey CLT buildings is proposed. The approach is based on a simplified phenomenological model where the behaviour of the CLT system is reproduced by means of an equivalent elastic modulus assigned to the CLT wall in order to account for both the connections and panel deformability. Phenomenological modelling aims to reproduce faithfully the global response of the structural system in terms of principal elastic period, internal forces in the connection elements and inter-storey drifts. Results of a multy-parametric analyses carried out on different CLT walls, deigned considering increasing level of seismic intensity, are presented and discussed. A design abacus that allows designers for a direct implementation of the proposed phenomenological model and therefore an easy and efficient seismic analysis of a CLT building is finally proposed.

KEYWORDS: Cross-Laminated Timber, CLT building, numerical model, phenomenological modelling approach, seismic design, Timber structures

1 INTRODUCTION

Cross-laminated timber (CLT) is a material suitable to realize multi-storey earthquake-resistant buildings, characterized by timber lightness and by high in-plane strength and stiffness of the massive cross-laminated panel. For these reasons and due to simplicity and rapid execution, CLT buildings have become increasingly common over the last few years [1-2]. However, how to model the CLT buildings, especially under seismic actions, is still an open issue. Several researches study CLT panels mechanical behaviour under cyclic and seismic actions [3-4]; another important discussed topic is related to the panels assembling [5-9] and the presence of openings [10-11]. Connection characterization is a crucial aspect in order to obtain proper input data for the numerical models [12-13]. Results of the different modelling approaches available in literature demonstrate to be quite heterogeneous and do not allow to draw reliable outcomes especially for the case of linear analyses of buildings. Two main modelling approaches are typically adopted in literature for linear analyses of CLT buildings: the first one is a *component model* (*CM*), which adopts elastic springs for connections and elastic elements for the CLT panel generally represented as a lattice grid or as a 2D continuum, while the second one is a simplified *phenomenological model* (*PM*), where the behaviour of the system is reproduced by means of a conventional equivalent elastic stiffness assigned to the CLT wall and capable of accounting for the deformability of the CLT panel and connections assembly [14]. *CM* is typically adopted in the research field and involves a high computational effort since each component of the CLT system must be modelled and properly calibrated. After proper calibration, CM allows to account for the tension-shear behaviour of the connection elements [15-16]. Differently, the *PM* is easier and faster to use respect to the *CM* and is typically adopted by practitioners since commercial software permits to implement the letter straightforward. The aim of the present work is to suitably calibrate the equivalent stiffness that has to be assigned to CLT panels in a *PM* in order to reproduce the seismic behaviour of the entire CLT building. To provide reliable estimation of the equivalent stiffness for the *PM*, different case study configurations have been analysed varying the significant parameters controlling the building response such as number of storeys, connection pattern, geometry, wall slenderness. Results of the performed analyses are used to propose a design abacus that permits an easy implementation of a phenomenological models of a real CLT building by practitioners.

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2 CALIBRATION PROCEDURE

Numerical response spectrum analyses have been conducted, comparing results of *CM* and *PM* in order to calibrate the correct equivalent stiffness (E_{eq}) to be assigned to CLT panels in the simplified phenomenological approach (Figure 1). Component-level (CM) modelling approach requires the calibration of constitutive laws for each component (CLT and connections) [17]. In detail CLT panels are modelled as an isotropic material (modulus of elasticity given by the weighted mean values of modulus in the parallel and perpendicular direction to the grain [18]) while connections are implemented as elastic springs (stiffness obtained from experimental tests).The PM modelling approach, at the opposite, disregards the contribution to the structural response given by each component of the system. Connection elements are not directly included in FE model and CLT panels are modelled assigning an equivalent elastic stiffness (i.e. modulus of elasticity) able to account for the deformability contributions of the connections and the panel itself.

In this work the equivalent elastic stiffness to be assigned to different configuration of CLT panels of the *PM* has been calibrated with an iterative procedure. In particular it was minimized an objective function which accounts for the difference between the value of certain control parameters (e.g. principal vibration period T_1, top displacement, inter-storey drift etc..) obtained with the *CM* and those obtained with the correspondent *PM* for the different building configurations.

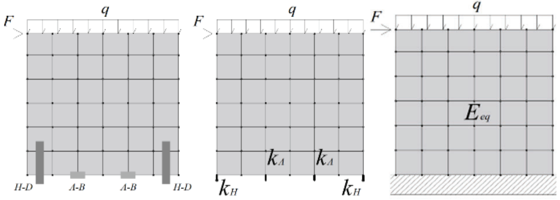

Figure 1: *Real configuration (left) component-level approach (centre) and phenomenological approach (right)*

A multi-parametric analysis was performed and an ad-hoc iterative procedure was implemented in order to provide a reliable definition of the equivalent modulus of elasticity (E_{eq}) to use in the modelling phase.

The iterative procedure starts selecting a certain shear-wall configuration characterized from a given geometry (length, height and thickness of the walls) and a given seismic mass and seismic intensity. The numerical-based approach consists in the iterative calibration procedure described below and schematized in Figure 2.

STEP 1 - definition of the connection pattern necessary to satisfying the different shear-walls configuration in terms of strength and deformability requirement;

STEP 2 - implementation of CM according to Polastri and Pozza [19]. Execution of the linear dynamic analysis to define the values of key parameters to be used for the subsequent calibration of the PM: principal vibration period (T_1^{CM}), base shear (V^{CM}), top displacement (δ^{CM}) and inter-storey drifts ($drift^{CM}$).

STEP 3 - consisted in the setting of the equivalent E_{eq} modulus of the CLT walls at each floor. It has been done thanks an implementation of PM performed with a linear dynamic analysis. The parameters taking into consideration in this analysis are: principal vibration period (T_1^{PM}), base shear (V^{PM}), top displacement (δ^{PM}) and nter-storey drifts ($drift^{PM}$).

ITERATIVE STEP - in the end the goal of this iterative calibration is the evaluating of equivalent modulus of elasticity (E_{eq}) in order to minimize the difference between the selected control parameters ($\Delta_j=Xj^{CM}-X_j^{PM}$). The iterative procedure ended when the comparison is acceptable ($\Delta_j<\Delta_{j\_LIMIT}$) providing a reliable estimation of the equivalent elastic module E_{eq} to be used in the phenomenological approach.

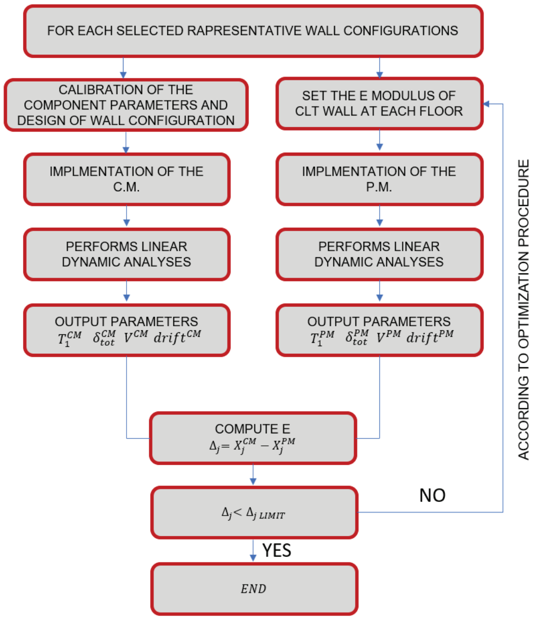

Figure 2: *Scheme of the conceptual iterative procedure for calibration of Eeq.*

The proposed methodology permit to overcome the inaccurate way of the behaviour evaluation of a simplified PM approach giving to a practitioner an extremely easier procedure of modelling thanks a calibration of a E_{eq} suitable for linear seismic analysis.

3 MULTI-PARAMETRIC FE ANALYSES

Numerical models of CLT walls were created using SAP2000 [20] Finite element code, Figure 3. A multi-parametric analysis was conducted considering the following variables: number of floors (3-5-7), base length of CLT panels (L=2,0m; 4,0m; 6,0 m), inter-storey height (assumed equal to 3m), seismic zone and seismic mass. All CLT wall configurations were modelled in 2-D

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according to both a component-level approach and a phenomenological approach.

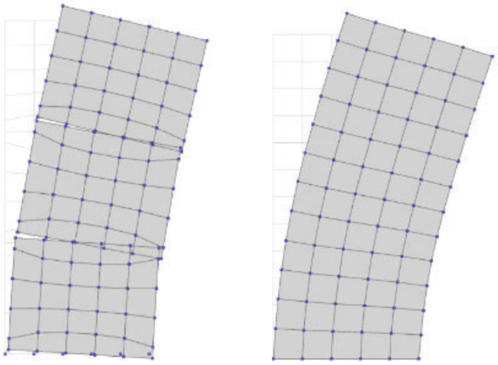

Figure 3: *Example of 3 storeys CLT wall implemented with CM (left) and PM (right)*

The earthquake action was calculated according to Eurocode 8 [9], using design spectra obtained with C soil type, a force modification factor q equal to 1.6. Two increasing levels of seismic intensity have been considered, respectively represented by PGA=0,25g (Low PGA) and 0,35g (High PGA).

Table 1 reports, for each considered configuration, the seismic mass on the wall at different floors.

Table 1: *Seismic mass at each level for each configuration.*

	L=2m		*L=4m*		*L=6m*	
Level	*High Mass* [t]	*Low Mass* [t]	*High Mass* [t]	*Low Mass* [t]	*High Mass* [t]	*Low Mass* [t]
Intermediate floors	3,8	5,6	7,6	11,3	11,4	16,9
Roof floor	1,9	2,8	3,8	5,65	5,7	8,45

Considering the two mass levels and the two seismic zones, a total of 32 different configurations were analysed.

Different pattern of connection specifically designed with regard to both resistance and deformability limit states characterized the different studied configurations. In the design the following connections were considered: WHT340-WHT620 and TTF200-TCF200, Hold-Down and Angle Bracket connection type, respectively. Table 2 reports the mechanical characteristics of the connections in terms of strength and stiffness. It is worth nothing that, for increasing number of storeys and for increasing level of seismic intensity it is necessary to use a larger the number of connectors in order to verify the structure.

Table 2*: Strength and stiffness of metal connection used in the analysis.*

Metal connector	WHT340	WHT620	TTF200	TCF200
Elastic siffness (kN/mm)	5,70	13,25	8,21	8,48
Design force (kN)	46,20	93,70	39,10	39,10

CLT panels were modelled with iso-parametric four-node quadrilateral membrane F.E. in both modelling approaches. In component-level approach (CM) the adopted values for elastic parameters, E=6600 MPa, v=0,35, were given by the weighted mean values of modulus in the parallel and perpendicular direction to the grain [8]. Connection elements (Hold-Down and Angle bracket) were modelled as linear elastic springs with stiffness derived from available experimental tests [ref]. In the *PM*, elastic stiffness of CLT walls was iteratively varied (i.e. reduced respect to the one used for the *CM*) in order to fit the global behaviour obtained with the *CM* by minimizing an objective function including the following control parameters: first vibration period T_1, top displacement, inter-storey drift and base shear force.

4 RESULTS AND DISCUSSION

Results obtained from the CM approach for all the considered configurations are presented in terms of fundamental elastic period (T_1), peak base shear forces at the Ultimate Limit State (ULS), maximum inter-story drift and top displacements at the Serviceability Limit State (SLS). These results are used as reference values for the calibration of the PM according to the proposed calibration procedure.

Figure 4 depicts the peak base shear forces on angle brackets at the ULS for each configuration. It is possible to observe how in several configurations, as the number of floors increases, the shear forces at the base varies slightly.

Figure 5 reports for all the examined shear-wall configurations the values of the principal elastic period. It is possible to observe how wall configurations with short walls and with a connections pattern related to low PGA, have high principal elastic periods T_1. Another parameter that greatly influences the period is represented by the slenderness of the wall. In fact, walls with high slenderness show greater periods of vibration than walls with less slenderness.

Figure 6 shows how an increase in the height of the building leads to high top displacements. For this reason the design requires the use of multiple Hold-Downs (more than two Hold Downs placed one-near-to the other at a corner of a CLT panel)in order to stiffen the structure and to reduce lateral displacements and inter-storey drifts (Figure 7).

Results assessed using the CM approach, on parametric wall configurations (results reported from Figure 4 to Figure 7), have been used in order to calibrate a set of E_{eq} following the optimization procedure previously described. The maximum errors on the significant control parameters ($\Delta_j = Xj^{CM} - X_j^{PM}$), obtained from the iterative procedure, are always lower than 5% confirming the effectiveness of the obtained equivalent modules E_{eq}.

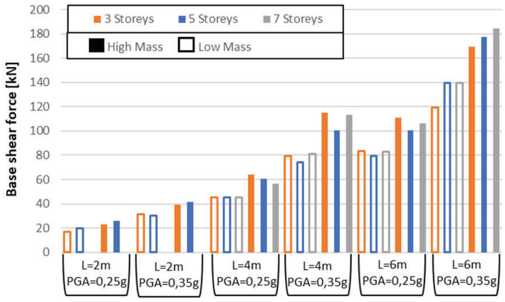

Figure 4: *Base shear force for each configuration*

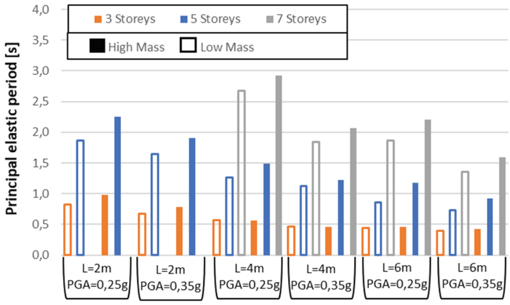

Figure 5: *Principal elastic period T1 for each configuration*

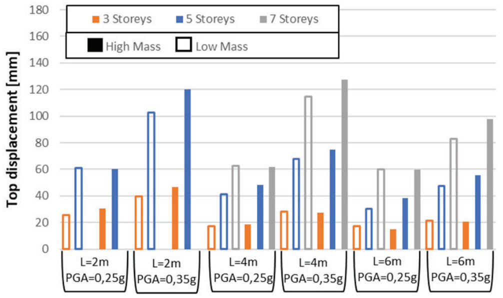

Figure 6: *Top displacement for each configuration*

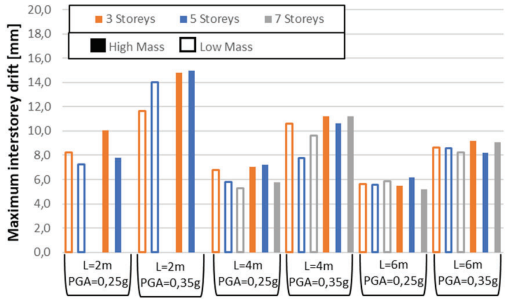

Figure 7: *Maximum inter-storey drift for each configuration*

Results were processed to define the suitable equivalent E modulus (E_{eq}) of the CLT wall as a function of: building geometry, seismic mass and seismic intensity. Obtained equivalent E modulus values (times the wall thickness), to be assigned to the wall of first floor (E_1) in case of a 3-storey building, are reported in Figure 8.

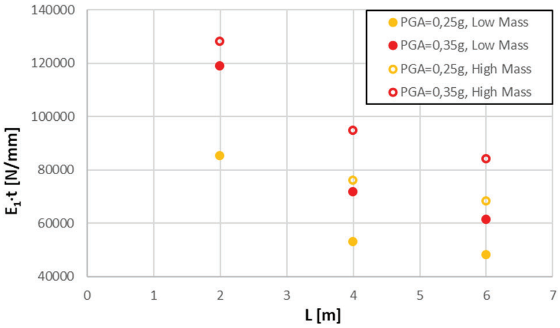

Figure 8: *Example of equivalent module to be assigned to the wall of first floor (E_1) for 3 storeys CLT structure*

A preliminary analysis of the results demonstrates the possibility to adopt a linear correlation between the equivalent stiffness of the wall at the level zero ($E_{eq,0}$) and the geometric proprieties of the shear-wall in terms of slenderness (λ) that is defined as the ratio between the height (H) and the base length (L) of the wall λ=H/L. The aforementioned linear correlation, for the two previously defined level of mass and level of seismic intensity considered in the parametric study, is shown in Figure 9.

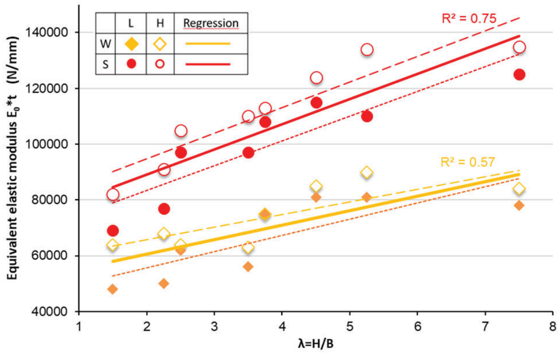

Figure 9*: Correlation between equivalent elastic modulus E_0 and slenderness of wall for different PGA, for different level of mass (Low: dotted lines and High: dashed lines) and level of seismic intensity (Weak: orange lines and Strong: red lines)*

The equivalent stiffness E_{eq0} assign to the wall of the level zero increases as the slenderness increases and is define as:

$$E_{\ eq0} \cdot t = a \cdot \lambda + b \tag{1}$$

Where: a=9044 and b=70987 for strong seismicity (continuous red line of Figure 8) while a=5184 and b=50325 for weak seismicity (continuous orange line of Figure 8). Based on the obtained results, the following function is proposed to correlate the Elastic module at the base level E_{eq0} and the elastic module at the i-th level $E_{eq,i}$.:

$$E_{\ eq,i} = E_{eq0}(1 - 0{,}31 \cdot n^{0.12}) \tag{2}$$

Where: n represent the floor number.

Figure 10 reports the mean and predicted values of equivalent stiffness of the upper floors ($E_{eq,i}$) scaled with respect to those of the ground floor ($E_{eq,0}$), at each level in case of a 3-storey building. It is possible to notice a knee adjustment in the stiffness values that can precisely predicted thanks to Equation 2.

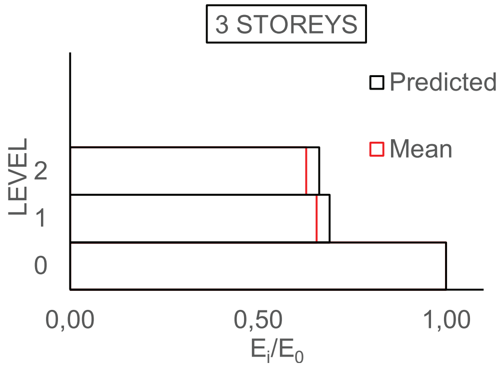

Figure 10*: Equivalent stiffness trend and prediction for 3 storey's structures.*

5 CONCLUSIONS

This study proposes a design-oriented numerical modelling approach for the prediction of the seismic response of multi-storey CLT buildings. It was proposed with the aim of faithfully reproduce the seismic behaviour of multi-storey CLT wall systems. The originality of the proposed phenomenological approach was the adoption of a properly calibrated wall equivalent stiffness accounting for both connections and panel deformability resulting in a real alternative to the more complex component modelling approach.

Results of the multi-parametric analyses and of the calibration procedure allowed the definition of a design abacus useful for a direct implementation of the phenomenological model in the analyses and design of a CLT building.

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