Timber shear walls: numerical assessment of the equivalent viscous damping

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Abstract

The seismic performance of timber shear walls is studied in this work, with focus on the energy dissipation ensured by sheathing-to-framing connections. Numerical non-linear analyses are carried out using a parametric numerical model developed in OpenSees and varying some basic design variables affecting the overall racking capacity of the wall, namely: aspect ratio, nails spacing and number of vertical studs. The equivalent viscous damping has been assessed by estimating the damping factor η through the Capacity Spectrum Method.

Keywords: **Timber shear walls; racking capacity; energy dissipation; equivalent viscous damping; Capacity Spectrum Method**.

Introduction

Timber light-framed constructions are widely used in North America, New Zealand and Northern Europe. These structural systems are very attractive for several reasons, including aesthetic pleasure, sustainability and rapid assembly of the elements. Moreover, they present a fairly good earthquake resistance, basically attributable to the high strength-to-density ratio of timber and to the remarkable ductility of joints with metal fasteners, which ensure reduced inertia forces and good energy dissipation, respectively.
Within this framework, a large amount of research on timber shear walls was carried out in the last decades. In fact, early researches on their mechanical performances date back to 1927 [1]. Existing studies on racking resistance, stiffness and ductility conducted by means of experimental, numerical and analytical methods have demonstrated the good mechanical performances of light-frame wall assemblies. Generally, timber has a poor dissipative capacity, unless it is properly reinforced [2], while the steel connections can ensure a good amount of plastic deformation and, as a consequence, a significant energy dissipation. In order to take into account this aspect, the designers can refer to the force-based design method proposed by EuroCode 8 [3], which allows to reduce the demand of the elastic acceleration spectrum by applying a reduction factor. Two approaches are commonly employed to this end, namely the N2 method [4] and the Capacity Spectrum Method [5][6]. The latter was considered in Ref. [7] to correlate structural damping and drift in timber-framed buildings. Overall, few efforts have been spent so far to analyze the mechanical behaviour and the energy dissipation of a single wall, and few parametric analyses are available that consider different wall configurations [8][9][10]. Therefore, an original parametric FE model has been implemented in the present work by means of the open-source software OpenSees [11] in order to assess the equivalent viscous damping of timber light-frame shear walls by estimating the damping factor η through the Capacity Spectrum Method.

Timber light-frame shear walls

Timber light-frame shear walls are employed in platform framing buildings. It is pointed out that only partially anchored walls will be investigated in this study. Details related to the classifications of timber shear walls can be found in [12] and [8] whereas the interested reader can refer to [13], [14] and [15] for detailed explanations about the differences between balloon and platform framing buildings. A timber light-frame shear wall is composed by vertical studs and horizontal joists (which belong to the frame) connected at their ends with internal constraints (typically modeled as hinges). This integrated system is braced by means of a sheathing panel, linked to the frame by using metal fasteners such as nails, screws and staples. The sheathing panel, in turn, can be built using different materials, like OSB, ply-wood, gypsum, glued laminated Guadua bamboo [16] and so on. The size of the sheathing panel, which could be used to brace one or both sides of the wall, sets the dimension of the frame. A typical size of a shear wall is 1.22 m × 2.44 m or 2.44 m × 2.44 m, whereas the framing elements cross-sections are about 38 mm × 89 mm and 38 mm × 140 mm for internal and external wall studs, respectively [17]. A typical configuration with both sides braced with a sheathing panel is shown in Fig. 1.

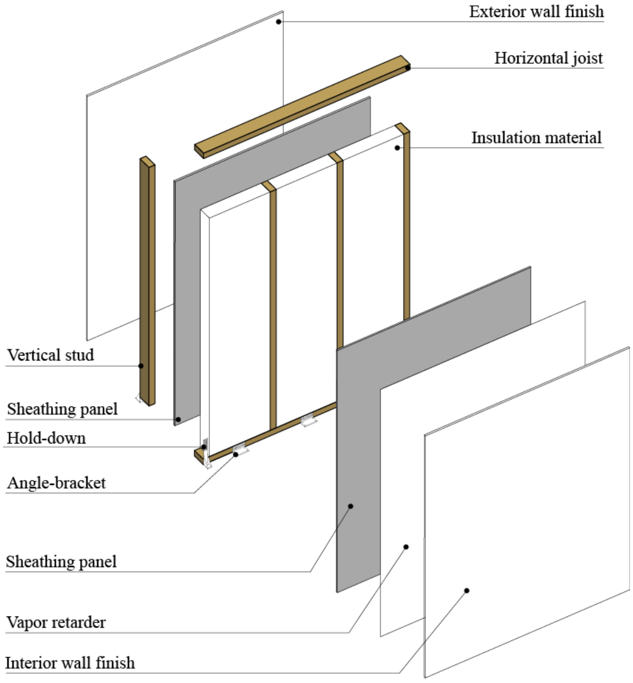

Figure 1. A typical configuration of a fully anchored timber light-frame shear wall braced on both sides, with further layers to improve thermal performances and fire-vapor resistances.

This integrated system is conceived to resist to different static, quasi-static and dynamic actions and its performances related to thermal insulation and fire-vapor resistances are often improved by adding further specific layers exploiting the thickness of external wall studs. Typically, the connections between framing elements and sheathing panels are made by means of 6D, 8D and 10D nails with thick shank placed on perimeter framing elements (the usual spacing is 50 mm, 75 mm or 100 mm) and intermediate studs. In the latter case, the spacing could be two or three times that on the perimeter studs because, as pointed out in Ref. [18], nails on the intermediate studs are only meant to prevent buckling of the sheathing panel and do not contribute to the racking capacity of the wall. In the so-called fully anchored timber shear wall, the connections with either the foundation or the lower storey shear wall are made by means of steel brackets, which prevent both lifting and horizontal relative sliding. The effects induced on the overall mechanical response by sheathing-to-framing connections have been investigated in [19][20][21]. Further details about base and stud-joist connections can be found in [22] and [20], respectively.

Numerical modeling and validation

To the best authors' knowledge, the finite element (FE) model developed in this work is the first numerical model of timber light-frame shear wall implemented in the open-source software OpenSees [11]. The model has been implemented in the TCL environment in such a way to allow rapid definition of all geometric parameters affecting the racking capacity of the shear walls, namely: *i)* panel size, *ii)* horizontal and vertical nails spacing, *iii)* number of vertical studs. Once these parameters are defined, the number of nodes and elements are updated automatically. For this FE model, it is assumed that the base and height of the shear wall are aligned with the x-axis and the z-axis, respectively. The frame has been modeled using elastic beam column elements, whereas non-linear coupled zero-length link elements are adopted to represent sheathing-to-framing connections. The sheathing panels are modeled by means of ShellMITC4 elements, whose mesh size depends on the nails spacing. In order to consider the constraints at the ends of framing elements acting as hinges, zero-length elements with a low stiffness value for the rotational degree of freedom along the y-axis have been used. Fully-fixed boundary constraints are assumed at the bottom corner nodes, as shown in Fig. 2, in order to assess the energy dissipation of the wall ensured only by the sheathing-to-framing connections.

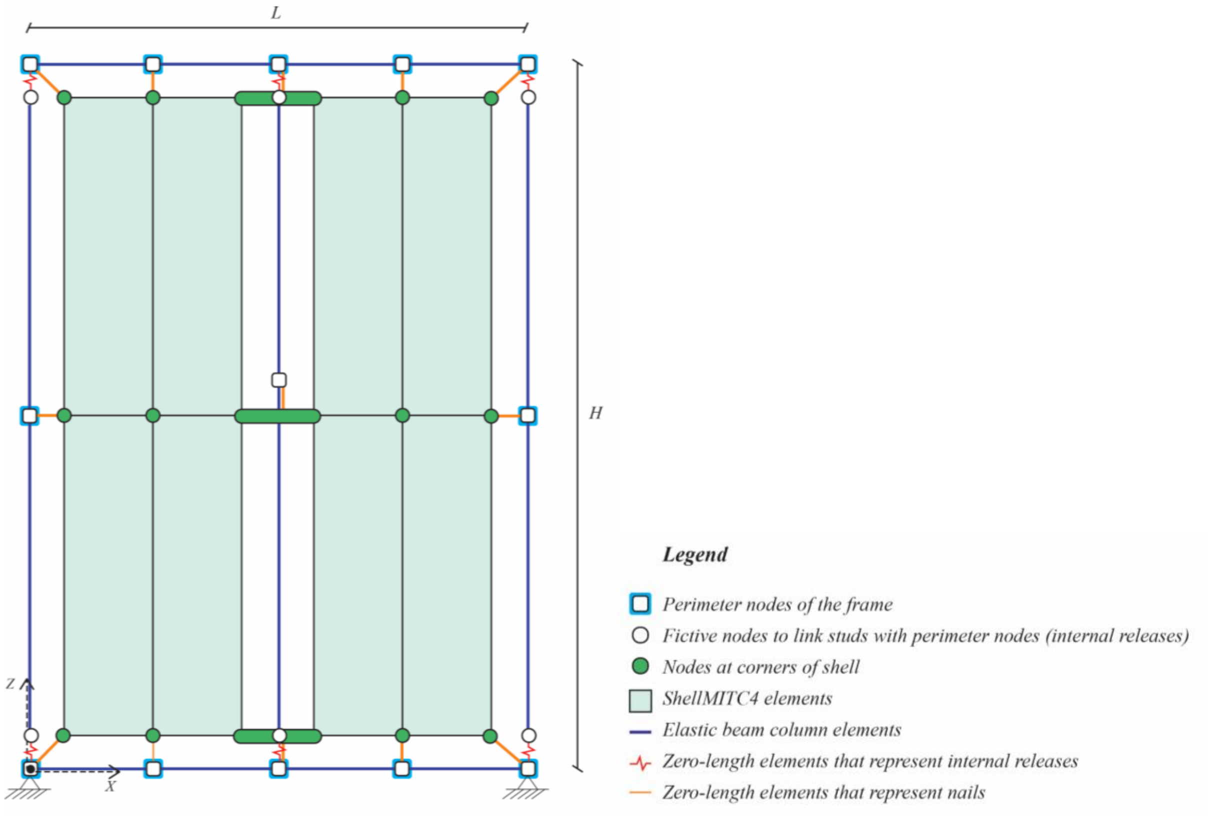

Figure 2. FE model implemented in OpenSees (5 × 3 nodes are considered in this scheme).

The reference wall configuration is the one considered in Ref. [23], which has the following geometrical features: width 1.8 m, height 2.6 m, nails spacing 50 mm, 4 vertical studs with internal releases (specimen PLS8). The mechanical characteristics used for the framing elements are referred to red spruce wood species with strength class C24, according to EN 14081-1 [24] and UNI EN 338 [25]. The SAWS mechanical model, originally proposed by Ref. [26] and developed in Ref. [27], has been adopted to simulate the behaviour of sheathing-to-framing connections. The corresponding model parameters are identified against the experimental result given for a single nail Φ 2.8 by Ref. [23]. In doing so, the non-classical identification methods presented in Ref. [28] have been used, adopting the following objective function:

$$f(\mathbf{x}) = \frac{1}{S \cdot \mathrm{var}\left(F^{\exp}\right)} \sum_{s=1}^{S} \left(F_s^{\,m}(\mathbf{x}) - F_s^{\,exp}\right)^2 \tag{1}$$

where **x** is the vector collecting the model parameters whereas F_s^m and F_s^{exp} are predicted and experimental force values, respectively. Moreover, s is the generic sample (S denotes the total number of samples) and var(F_s^{exp}) is the variance of the experimental force values. The comparison between experimental and identified force-displacement curves of a single nail is shown in Fig. 3, together with the comparison between experimental and predicted load-displacement curves of the reference wall. It is possible to observe that racking capacity and hysteretic cycles evaluated using the proposed numerical FE model are in good agreement with the outcomes of the experimental tests shown in Ref. [23].

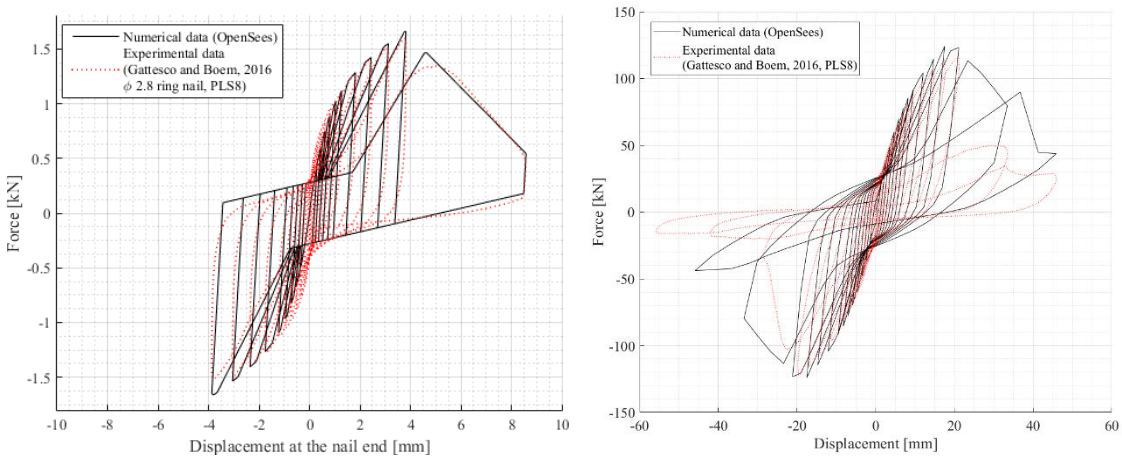

Figure 3. Identification of SAWS model parameters for the sheathing-to-framing connections and validation of the FE model: comparison between experimental and identified force-displacement curves of a single nail (left), comparison between experimental and predicted load-displacement curves for the reference wall (right).

Sensitivity analysis

Once identified the constitutive law of the sheathing-to-framing connections, the overall response in terms of hysteretic damping and racking capacity of different timber light-frame shear walls has been evaluated. A horizontal cyclic loading under displacement-controlled conditions has been applied. Aspect ratio (i.e., height-to-width ratio), horizontal and vertical nails spacing and number of vertical studs have been varied in order to quantify their influence. As pointed out in Ref. [8], the aspect ratio strongly influences the response of partially- and non-anchored walls. The contribution of shear deformation to storey displacements increases if the base of the shear wall is significantly larger than its height, as pointed out in Ref. [29]. Conversely, if the base is about 30% of the height, then the flexural behaviour is dominant. By observing the overall behaviour of the wall in parallel with the local behaviour of each nail, the following definitions are given:

1) the Life Safety Limit State is recognized to occur in correspondence of the racking strength peak, when all nails along the perimeter framing elements are yielded;
2) the Collapse Limit State is recognized to occur when the most stressed nail, usually at the bottom corner, reaches its failure displacement.

As a consequence, the following criterion was adopted: the amount of dissipated energy is evaluated from the force-displacement curve of a certain configuration of shear wall once the first nail reached a resistance decrement equal to 65%, according to the experimental data in Ref. [23].

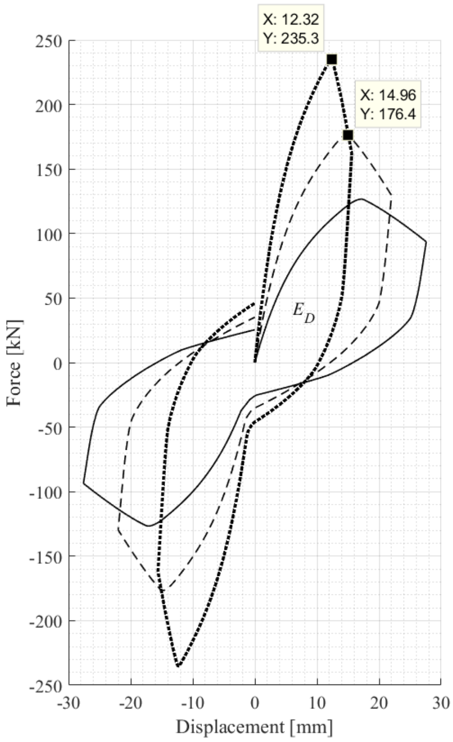

Figure 4. Influence of aspect ratio on the overall response of the wall:
1.4 (solid line, reference configuration),
1.0 (dashed line, square wall),
0.7 (dotted line, squat wall).

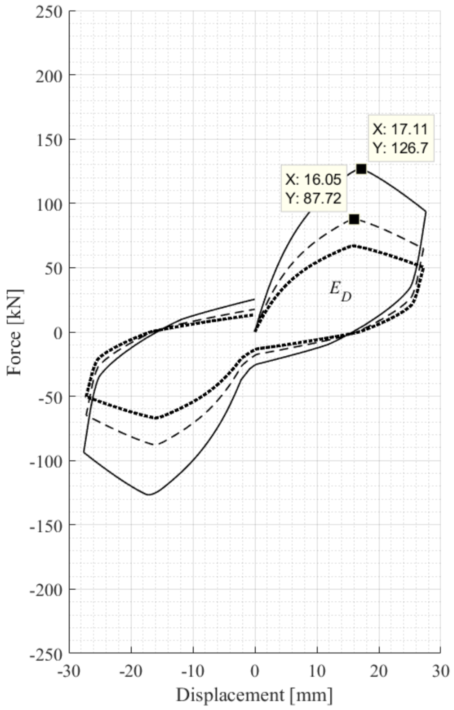

Figure 5. Influence of nails spacing on the overall response of the wall:
50 mm spacing (solid line, reference configuration),
75 mm spacing (dashed line),
100 mm spacing (dotted line).

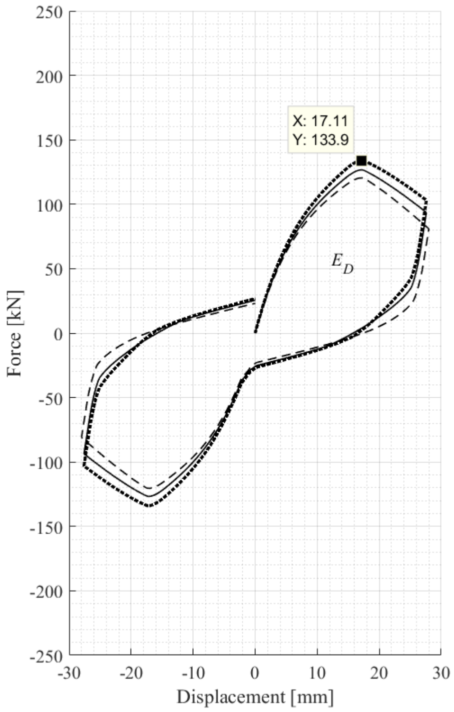

Figure 6. Influence of number of vertical studs on the overall response of the wall:
3 studs (dashed line),
4 studs (solid line, reference configuration),
5 studs (dotted line).

As shown in Fig. 4, the lower the aspect ratio, the higher the hysteretic damping and racking capacity. The relative rigid rotation of the sheathing panel with respect to the frame mostly stresses the nails near the corners, whereas the others remain in the elastic range. By varying horizontals and vertical nails spacing from 50 mm to 100 mm, it is possible to observe a reduction of the racking capacity (Fig. 5). Particularly, the reduced number of nails on the perimeter studs makes the overall system more flexible but leaving the ductility unchanged. Finally, the influence of the studs' number is shown in Fig. 6.

Equivalent viscous damping

A simplified way to take into account ductility or dissipative capacity of a structure in modern seismic design codes is based on the reduction of the elastic spectrum demand. The scaling of the elastic spectrum is function of an additional equivalent viscous damping ξ_{eq}, which is computed as follows:

$$\xi_{eq} = \frac{E_D}{4\pi E_{s0}} \tag{2}$$

where E_D is the dissipated energy in a single cycle, normalized to the elastic strain energy in a half cycle, E_{s0}. The total equivalent viscous damping ξ_{tot} is obtained by adding the inherent viscous damping $\xi_{0.05}$ (equal to 5%):

$$\xi_{tot} = \xi_{0.05} + \xi_{eq}. \tag{3}$$

The reduced spectrum is then obtained by using the damping correction factor η, which is computed as follows [3]:

$$\eta = \sqrt{\frac{10}{5 + \xi_{tot}}}\ . \tag{4}$$

The equivalent viscous damping as function of the drift value (defined as the ratio between horizontal displacement and wall height) for different wall configurations is given in Fig. 7.

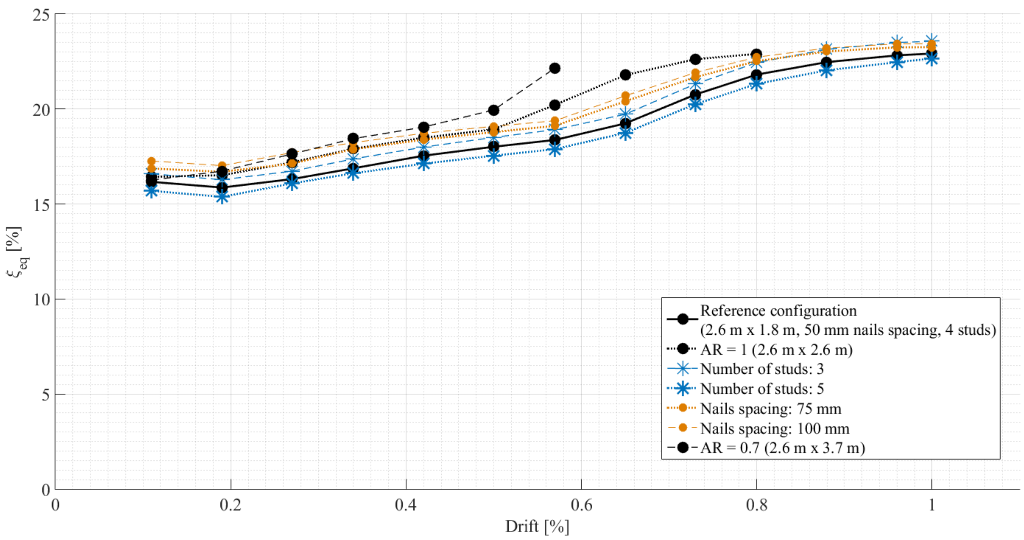

Figure 7. Equivalent viscous damping as function of drift for different wall configurations. The solid black line indicates the reference configuration: aspect ratio equal to 1.4, nails spacing equal to 50 mm and 4 vertical studs.

As shown in Fig. 7, the linear variation observed by Ref. [7] for wood framed buildings is fairly confirmed for timber walls as well. It can also be inferred that the energy dissipation strongly depends on the aspect ratio, thereby confirming the results in Ref. [8]. However, it is worth highlighting that the larger the wall size, the larger the number of vertical studs and the overall number of vertical nails: the resultant global system is stiffened. This is due to the fact that a lower plasticity level is reached by increasing the number of vertical studs and, consequently, the overall number of nails. Conversely, the number of yielded nails grows by reducing the number of vertical studs, and thus a higher amount of dissipated energy is achieved. Particularly, a higher amount of nails, especially on the intermediate studs, makes the overall system more resistant, preventing buckling of the sheathing panel, without providing a contribution in terms of plastic deformation and energy dissipation. By reducing the nails spacing, a stiffer wall is observed but a slightly lower value of the equivalent viscous damping is obtained. For the reference configuration (aspect ratio equal to 1.4, nails spacing equal to 50 mm, 4 vertical studs), the equivalent viscous damping is about 23%. This means that the value of the total equivalent viscous damping required to estimate the reduction of the elastic demand spectrum is about of 28% (assuming an inherent viscous damping equal to 5%). Hence, the resulting η factor is about 0.55. A summary of the results related to the variation of racking capacity, total equivalent viscous damping and damping factor, with respect to the geometric input parameters used in the parametric analyses, is shown in Fig. 8.

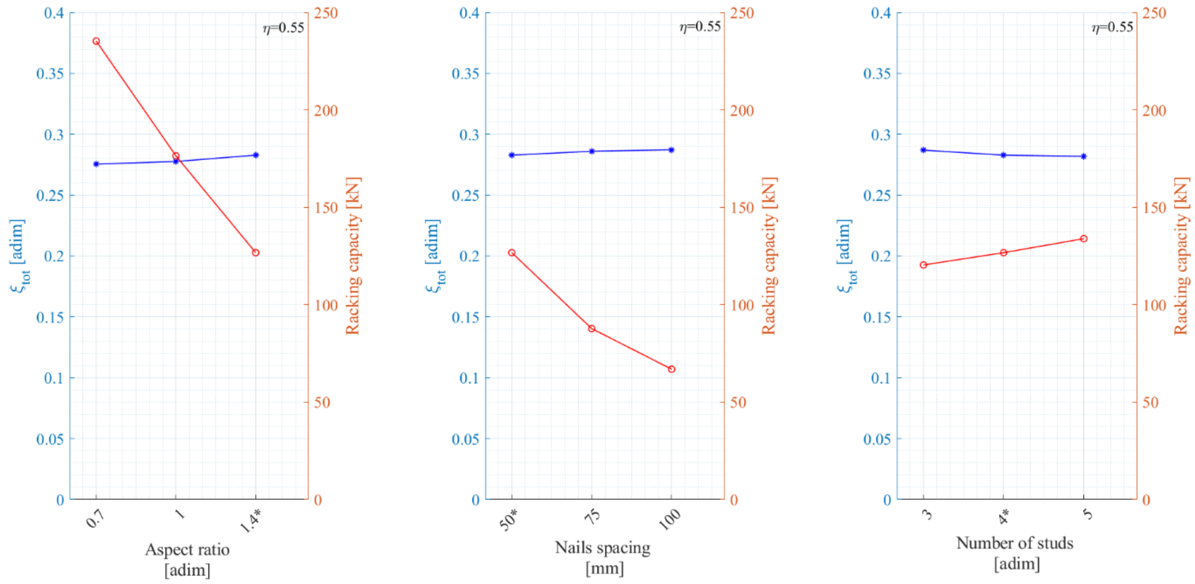

Figure 8. Variation of racking capacity (red), total equivalent viscous damping (blue) and damping factor η for different values of aspect ratio, nails spacing and number of vertical studs.
The reference configuration has aspect ratio equal to 1.4, nails spacing equal to 50 mm and 4 vertical studs
(the corresponding values are marked with the symbol *).

Conclusions

In this work an original parametric FE model for timber light-frame shear walls implemented in OpenSees is presented. It includes the following elements: *i)* elastic beam column for the framing elements, *ii)* non-linear coupled zero-length link elements for the sheathing-to-framing

connections, *iii)* zero-length elements for joints connecting framing elements, and *iv)* ShellMITC4 elements for the sheathing panels.
The numerical model has been validated considering the data carried out from experimental tests presented in Ref. [23]. The SAWS mechanical model, originally proposed by Ref. [26] and developed in Ref. [27], has been calibrated using the available experimental data and then implemented in order to simulate the behaviour of a single nail. Parametric analyses have been used to assess the influence of some basic design variables on racking capacity and equivalent viscous damping. Final results have demonstrated that the proposed model can be effectively used to carry out non-linear analyses and to calibrate the damping factor η in use within the Capacity Spectrum Method.

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