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TIMBER SHEAR WALLS: NUMERICAL ASSESSMENT OF THE EQUIVALENT VISCOUS DAMPING

Giorgia Di Gangi[1(*)], Cristoforo Demartino[2], Giuseppe Quaranta[1], Marco Vailati[1], Giorgio Monti[1,2]
[1]Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Italy
[2]College of Civil Engineering, Nanjing Tech University, PR China
[(*)]*Email:* giorgia.digangi@uniroma1.it

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, 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 the timber and to the remarkable ductility of the 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, research on their mechanical performances dates back to 1927 (Peterson, 1983). 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 (Jorissen and Fragiacomo, 2011), 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 (EN1998-1-1:2003), which allows to reduce the ordinates of the elastic acceleration spectrum by applying a reduction factor. Two approaches are commonly employed to this end, namely the N2 method (Fajfar, 1999) and the Capacity Spectrum Method (CSM) (Freeman, 1978 and 1998). The latter was considered in (Filiatrault *et al.*, 2003) to correlate structural damping and drift in timber-framed building. Overall, few efforts have been spent so far to analyze the mechanical behavior and the energy dissipation of a single wall, and few parametric analyses are available that consider different wall configurations (Salenikovich and Dolan, 2003; Dhonju *et al.*, 2017). Therefore, an original parametric FE model has been implemented in the present work by means of the open-source software OpenSees (McKenna and Fenves, 2001) in order to assess the equivalent viscous damping of timber shear walls by estimating the damping factor η through the Capacity Spectrum Method.

TIMBER SHEAR WALLS

Timber 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 (Porteous and Kermani, 2013) and (Salenikovich and Dolan, 2000), whereas the interested reader can refer to (Kolb, 2008), (Mehta *et al.*, 2009) and (Wacker, 2010) for detailed explanations about the differences between balloon and platform framing buildings. A light-framed timber 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 (Varela *et al.*, 2012) 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 (Wang *et al.*, 2017). A typical configuration with only one side braced with a sheathing panel is shown in Figure 1.

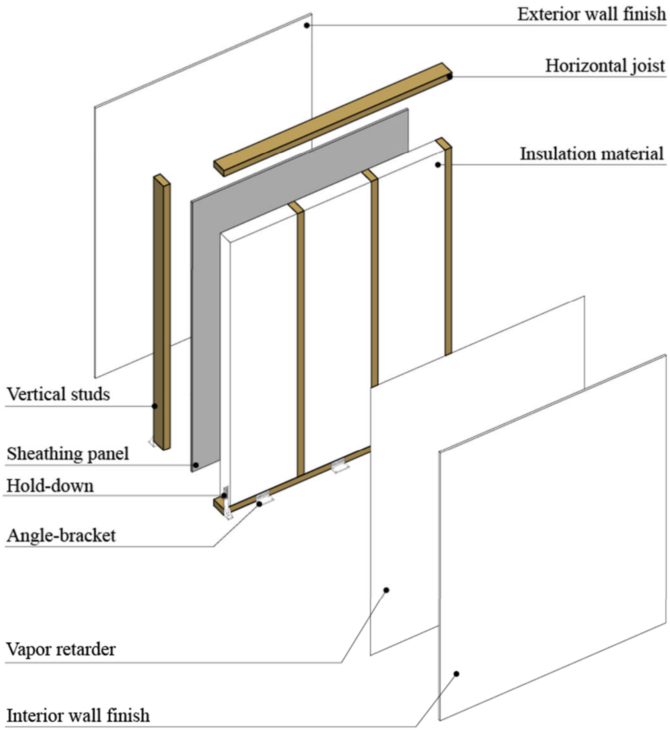

Fig. 1 - A typical configuration of a fully anchored timber shear wall braced on one side, with further layers to improve thermal performances and fire-vapor resistances.

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 connection 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 (Källsner and Girhammar, 2009), 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 (Sartori and Tomasi, 2013; Humbert *et al.*, 2014; Germano *et al.*, 2015). Further details about base and stud-joist connections can be found in (Gavric *et al.*, 2015) and (Humbert *et al.*, 2014), 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 shear wall implemented in the open-source software OpenSees (McKenna and Fenves, 2001). 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: panel size, horizontal and vertical nails spacing, and 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 elements have been modeled using one-dimensional elastic beam column elements, whereas non-linear zero-length link elements are adopted to represent sheathing-to-framing connections. The sheathing panel is modeled by means of two-dimensional, stiff plane-stress elements (ShellMITC4), 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 Figure 2.

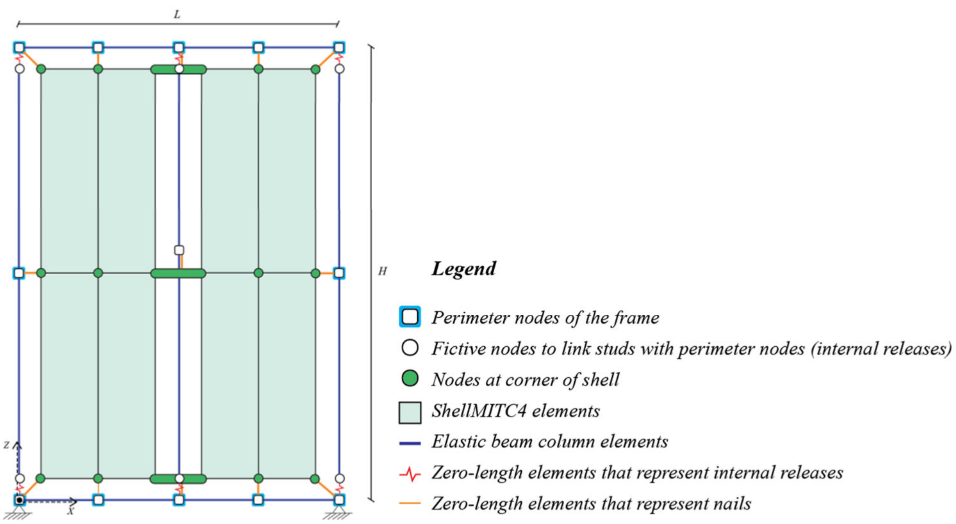

Fig. 2 - FE model implemented in OpenSees (5 × 3 nodes are considered in this scheme).

The reference wall configuration is the one considered in (Gattesco and Boem, 2016), which has the following geometrical features: width 1.8 m, height 2.6 m, nails spacing 50 mm, 4 vertical studs without internal releases. The mechanical characteristics used for the framing elements are referred to red spruce wood species with strength class C24 (EN 14080, 2013 and UNI EN 338, 2009). The displacement level selected for the analysis is equal to 21 mm to consider stable hysteresis cycles of the nails, without strength and stiffness degradation. The SAWS mechanical model, originally proposed by (Foschi, 1977) and developed in (Folz and Filiatrault, 2001), has been adopted to simulate the behavior of sheathing-to-framing connections. The corresponding model parameters are identified against the experimental result given for a single nail Φ 2.8 by Gattesco and Boem (2016). In doing so, the non-classical identification methods presented in (Quaranta *et al.*, 2010) have been used, adopting the following objective function:

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

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 Figure 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 (Gattesco and Boem, 2016).

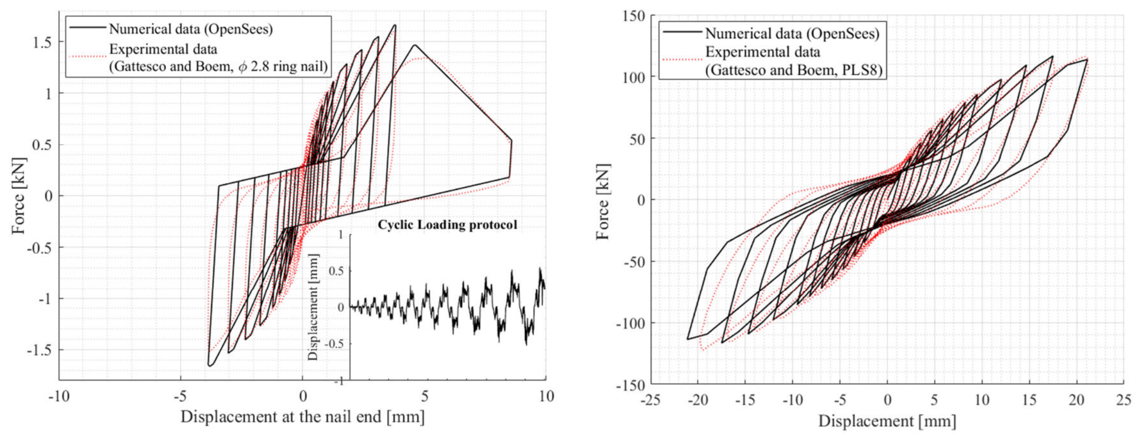

Fig. 3 - Identification of SAWS model parameters for the sheathing-to-framing connections and validation of the FE model: comparison between experimental and identified force-displacement curves of a single nail (left), comparison between experimental and predicted load-displacement curves for the reference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

SENSITIVITY ANALYSIS

Once identified the constitutive law of the sheathing-to-frame connections, the overall response in terms of hysteretic damping and racking capacity of different timber 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 (Salenikovich and Dolan, 2000), the aspect ratio strongly influences the response of partially- and non-anchored walls, and the peak load is achieved when the first sheathing nail in the tension corner is torn through the panel edge. 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 (Anil *et al.*, 2017). Conversely, if the base is about 30% of the height, then the flexural behavior is dominant.

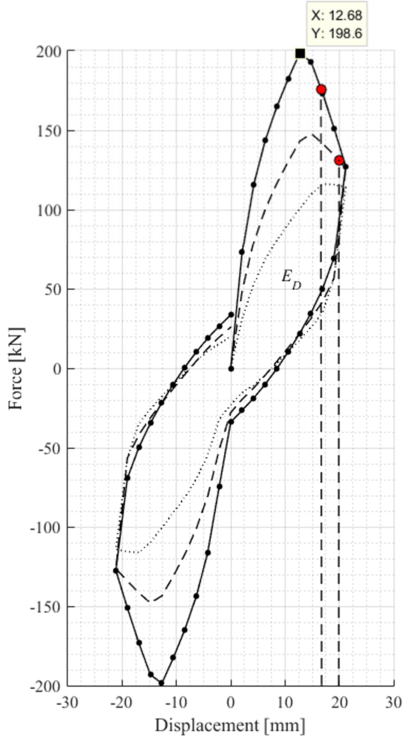

Fig. 4 - Influence of aspect ratio on the overall response of the wall: 1.4 (dotted line, slender wall, hysteretic damping equal to 19%),; 1.0 (dashed line, square wall, hysteretic damping equal to 23%); 0.7 (solid line, squat wall, hysteretic damping equal to 32%).

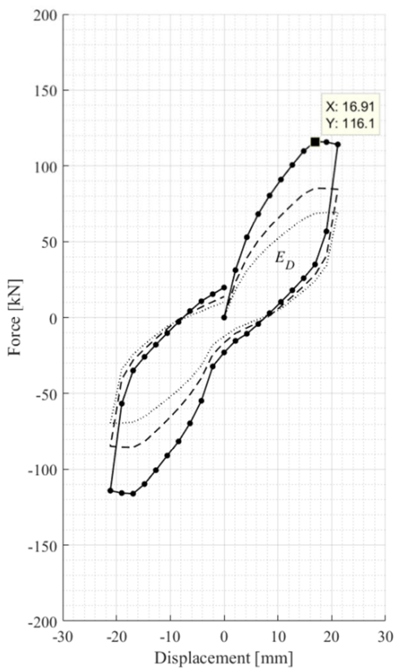

Fig. 5 - Influence of nails spacing on the overall response of the wall: 50 mm spacing (solid line, hysteretic damping equal to 19%); 75 mm spacing (dashed line, hysteretic damping equal to 18%); 100 mm spacing (dotted line, hysteretic damping equal to 17%).

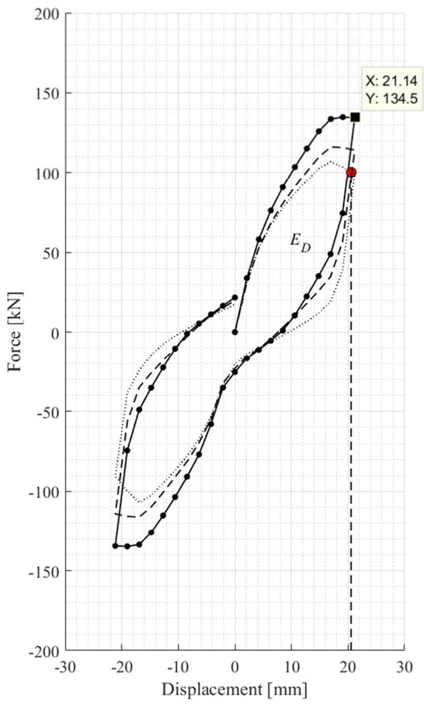

Fig. 6 - Influence of number of studs on the overall response of the wall: 3 studs (dotted line, hysteretic damping equal to 22%); 4 studs (dashed line, hysteretic damping equal to 19%); 5 studs (solid line, hysteretic damping equal to 17%).

As shown in Figure 4, the lower the aspect ratio, the higher the hysteretic damping and racking capacity. The red marker is a control point that identifies force and displacement values of the wall corresponding to a resistance decrease equal to 65% for at least one nail, according to the experimental data in (Gattesco and Boem, 2016). This is a control parameter that allows to check the deformation level achieved by the whole system. 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 racking capacity and hysteretic damping at the same displacement level (Figure 5). Particularly, the reduced number of nails on the perimeter studs makes the overall system more flexible. Finally, the influence of the studs number is assessed in Figure 6. Here, it is worth to notice that no nail achieves a resistance decrease of 65%, except in the configuration with 3 vertical studs.

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 ordinates. According to the Capacity Spectrum Method, 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 (Eurocode 8, EN1998-1-1, 2003; NTC-08), which is computed as follows:

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

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 Figure 7. It is remarked that the displacement level selected for the analysis is equal to 21 mm, in such a way to obtain stable hysteresis cycles of the nails, without strength and stiffness degradation.

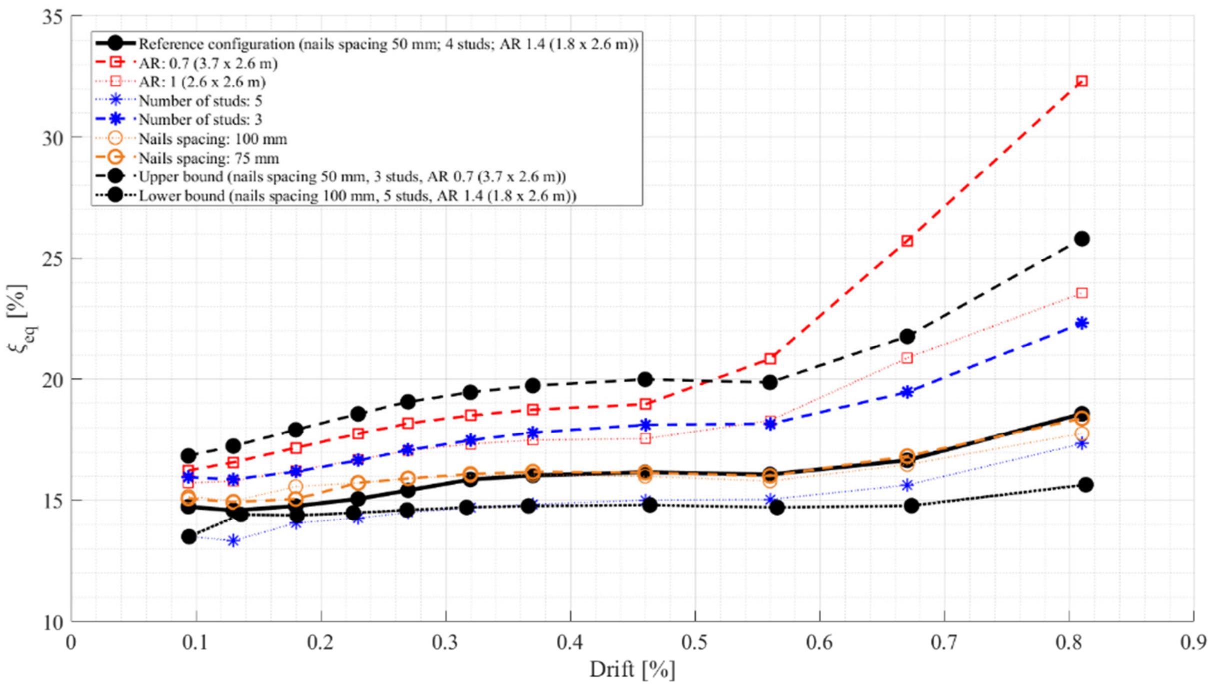

Fig. 7 - Equivalent viscous damping as function of the drift for different wall configurations. The solid black line indicates the reference configuration: aspect ratio equal to 1.4, nails spacing equal to 50 mm and 4 vertical studs.

As shown in Figure 7, the linear variation observed by Filiatrault *et al.* (2003) 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 (Salenikovich and Dolan, 2000). 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: with respect to the values shown in Figure 7, therefore, a reduction of the amount of dissipated energy is thus expected. 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 higher value of the equivalent viscous damping is obtained, due to the gradual resistance reduction of the nails. For the reference configuration (nails spacing equal to 50 mm, 4 vertical studs, aspect ratio equal to 1.4), the equivalent viscous damping is about 19%. This means that the value of the total equivalent viscous damping required to estimate the reduction of the elastic demand spectrum is about of 24% (assuming an inherent viscous damping equal to 5%). Hence, the resulting η factor is about 0.59. 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 Figure 8.

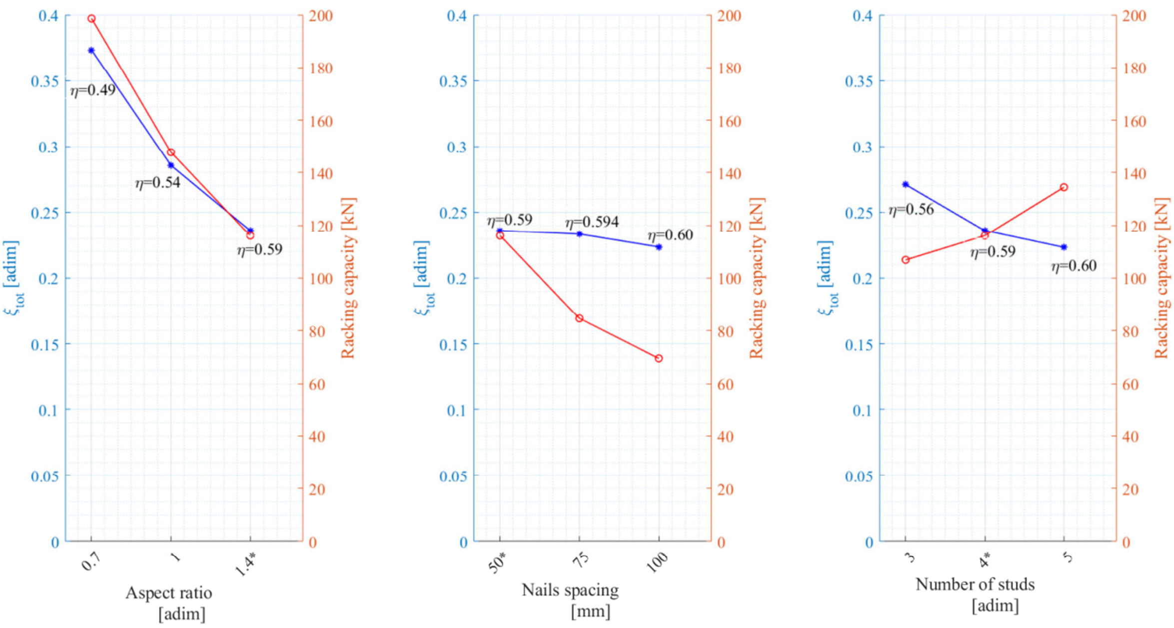

Fig. 8 - Variation of racking capacity, total equivalent viscous damping and damping factor for different values of aspect ratio, nails spacing and number of vertical studs. The reference configuration has nails spacing equal to 50 mm, 4 vertical studs, aspect ratio equal to 1.4 (the corresponding values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

CONCLUSIONS

The present work presented an original parametric FE model for timber shear walls implemented in OpenSees. It includes the following elements: (i) elastic beam column elements for the framing elements, (ii) nonlinear zero-length elements to represent the sheathing-to-framing connections, (iii) zero-length elements for the internal releases at the ends of the framing elements, and (iv) stiff plane-stress shell elements for the sheathing panel.

The validation of this numerical model has been performed considering the data carried out from experimental tests presented in (Gattesco and Boem, 2016). The SAWS mechanical model, originally proposed by Foschi (1977) and developed in (Folz and Filiatrault, 2001), has been implemented in order to simulate the behavior of a single nail, and its parameters have been calibrated using the available experimental data. Parametric analyses have been used to assess the influence of the timber shear wall configuration on racking capacity and equivalent viscous damping. Final results have demonstrated that the proposed model can be effectively used to carry out nonlinear analyses and to calibrate the damping factor η in use within the Capacity Spectrum Method.

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REFERENCES

[1] Anil Ö, Togay A, Işleyen Ü K, Döngel N, Söğütlü C. Effect of Timber Type and Nail Spacing on the Hysteretic Behavior of Timber-Framed Shear Walls with Openings, in International Journal of Civil Engineering, 2017, pp. 1-18.

[2] Dhonju R, D'Amico B, Kermani A, Porteous J, Zhang B. Parametric evaluation of racking performance of platform timber framed walls, Structures, 2017, 12, pp. 75-87.

[3] EN1998-1, Eurocode 8: Design Provisions for Earthquake Resistance of Structures, Part 1.1: General rules, seismic actions and rules for buildings, CEN - European Committee for Standardization TC250/SC8, 2003.

[4] EN 14080, Timber structures - glued laminated timber and glued solid timber, B/518, 2013.

[5] Fajfar P. Capacity spectrum method based on inelastic spectra, Earthquake Engineering and Structural Dynamics, 1999, 28(9), pp. 979-993.

[6] Filiatrault A, Isoda H, Folz B. Hysteretic damping of wood framed buildings, Engineering Structures, 2003, 25(4), pp. 461-471.

[7] Folz B, Filiatrault A. Cyclic Analysis of Wood Shear Walls, in Journal of Structural Engineering, 2001, 127(4), pp. 433-441.

[8] Foschi, RO. Analysis of wood diaphragms and trusses - Part 1:Diaphragms, Canadian Journal of Civil Engineering, Ottawa, 1977, 4(3), pp. 345-362.

[9] Freeman SA. Prediction of Response of Concrete Buildings to Severe Earthquake Motion, in Douglas McHenry International Symposium on Concrete and Concrete Structures, SP-55, American Concrete Institute, Detroit, Michigan, 1978, pp. 589-605.

[10] Freeman SA. The Capacity Spectrum Method as a Tool for Seismic Design, in Proceedings of the 11th European conf. on earthquake engineering, Paris, 1998, pp. 6-11.

[11] Gattesco N, Boem I. Stress distribution among sheathing-to-frame nails of timber shear walls related to different base connections: Experimental tests and numerical modelling, in Construction and Building Materials, 2016, 122, pp. 149-162.

[12] Gavric I, Fragiacomo M, Ceccotti A. Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures, in Materials and Structures, 2015, 48(6), pp. 1841-1857.

[13] Germano F, Metelli G, Giuriani E. Experimental results on the role of sheathing-to-frame and base connections of a European timber framed shear walls, Construction and Building Materials, 2015, 80, pp. 315-328.

[14] Humbert J, Boudaud C, Baroth J, Hameury S, Daudeville L. Joints and wood shear walls modelling I: Constitutive law, experimental tests and FE model under quasi-static loading, Engineering Structures, 2014, 65, pp. 52-61.

[15] Jorissen A, Fragiacomo M. General notes on ductility in timber structures, in Engineering and Structures, 2011, 33(11), pp. 2987-2997.

[16] Källsner B, Girhammar UA. Analysis of fully anchored light-frame timber shear walls-elastic model, in Materials and Structures, 2009, 42(3), pp. 301-320.

[17] Källsner B, Girhammar UA. Plastic models for analysis of fully anchored light frame timber shear walls, in Engineering and Structures, 2009, 31(9), pp. 2171-2181.

[18] Kolb J. Systems in Timber Engineering, Loadbearing Structures and Component Layers, Birkhauser, Basel - Boston - Berlin, 2008.

[19] McKenna F, Fenves G. The OpenSees Command Language Manual: version 1.2, Pacific Earthquake Engineering Center, Univ. of Calif., Berkeley, 2001.

[20] Mehta M, Scarborough W, Armpriest D. Building Construction, Principles, Materials and System, Prentice Hall - Pearson, New Jersey, 2009.

[21] NTC-08, Norme Tecniche per le Costruzioni, 2008, M.D. 2008/01/14.

[22] Peterson J. Bibliography on Lumber and Wood Panel Diaphragms, Journal of Structural Engineering, 1983, 109(12), pp. 2838-2852.

[23] Porteous J, Kermani A. Structural timber design to Eurocode 5, Blackwell Publishing Ltd, 2013, ISBN: 978-14051-4638-8.

[24] Quaranta G, Monti G, Marano GC. Parameters identification of Van der Pol-Duffing oscillators via particle swarm optimization and differential evolution, Mechanical Systems and Signal Processing, 2010, 24(7), pp. 2076-2095.

[25] Salenikovich A, Dolan JD. The racking performance of light-frame shear walls with various tie-down restraints, in Proceedings of the 6th World Conference on Timber Engineering, Canada, 2000, July-August.

[26] Salenikovich A, Dolan JD. The racking performance of shear walls with various aspect ratios. Part I. Monotonic tests of fully anchored walls, Forest Products Journal, Madison, 2003, 53.10, pp. 65-73.

[27] Sartori T, Tomasi R. Experimental investigation on sheathing-to-framing connections in wood shear walls, Engineering Structures, 2013, 56, pp. 2197-2205.

[28] UNI EN 338, Structural wood - strength classes, B/518, 2009.

[29] Varela S, Correal J, Yamin L, Ramirez F. Cyclic performance of glued laminated guadua bamboo-sheated shear walls, in Journal of Structural Engineering., 2012, 139(11), 2028-2037.

[30] Wang J, Demartino C, Xiao Y, Li Y. Thermal insulation performances of bamboo and wood-based shear walls in light-frame building, Energy and Buildings Journals, 2018 (accepted).

[31] Wacker J. Use of Wood in Buildings and Bridges, in Wood Handbook - Wood as an Engineering Material, chapt. 17, Forest Products Laboratory - United States Department of Agriculture Forest Service - Madison, Wisconsin, 2010.