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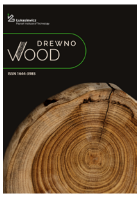

Effects of Different Types of Connections on the Dynamic Response of Wooden Frames – Experimental Study

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Timber buildings are resistant to dynamic loads due to their low weight and relatively high rigidity. However, the connections between wooden elements are the key elements of their rigidity. This study investigates how two common fasteners—nails and screws—affect the dynamic response of wooden frames. Experimental tests have been conducted on two different wooden frames. The first one is connected with nails, while the second one is connected with screws. Standard wall frame elements were subjected to harmonic excitation at various frequencies and displacement amplitudes. The research aimed to assess the impact of the typical structural fasteners used on the rigidity of the wooden frame in global terms. Experimental results indicate that replacing nails with screws significantly enhances the dynamic performance of wooden wall frames. The results show a very effective method of strengthening skeletal structures, which can be implemented at a low cost at the initial design and during the construction stage of the structures.

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Introduction

The safety and resistance of structures, particularly buildings, is a critical issue in the context of natural hazards such as earthquakes (Miari et al., 2019, 2021). Damages to building components during seismic excitations are the main reason for their failure, which further results in danger to human lives (Elwardany et al., 2017; Mochizuki et al., 1988; Sołtysik & Jankowski, 2013). This applies to all types of building technologies. However, the popularity of such building materials as concrete and steel means that the most common technologies in construction are centred on them. Also, in the sphere of seismic resistance of masonry structures, one of the main roles is played by the adopted design criteria, their experimental and theoretical foundations, as well as their practical consequences (Magenes, 2006). Many repair methods for masonry exist, such as additional reinforcement, steel frames, fibre composites, reinforced polymers, or adhesives (Kim et al., 2015; Kwiecień, 2015; Li et al., 2017; Linghoff et al., 2009; Shrive, 2006; Teng et al., 2012). Recently, however, there has been an increase in interest in timber frame construction technology in regions affected by earthquakes. The technology is easy and quick to install (Tomei et al., 2023). It also reduces construction time and makes it easier to adapt the facility to high energy standards and requirements of passive building. In addition to the well-known advantages of a wooden skeleton structure, a very important advantage above all is the low weight of the structure and relatively high

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rigidity, compared to other types of building materials (Gani et al., 2024; Mutlu et al., 2025; Sandoli et al., 2021). This makes the wooden structures very popular in seismically active areas. Advanced studies focused on the strength of wooden skeleton technology, including seismic resistance of wooden structures, are carried out in various research centres around the world. They cover topics such as identifying weak points and monitoring critical components during earthquakes. Previous works include experimental tests like shaking table studies (Becerra et al., 2025; Blomgren et al., 2019; Fang et al., 2025; Filiatrault et al., 2010; Heiduschke et al., 2009; Pei et al., 2019; Seo et al., 1999; Tachibana et al., 2025; Tsiavos et al., 2023), as well as numerical analyses (Jameel et al., 2013; Migda et al., 2019; Szczepański et al., 2016). Researchers carried out investigations on real structures as well as on structural elements and construction models (Bobra et al., 2012; Kasal, 2014; Sugiyama et al., 1988; Zhang et al., 2024). Others have studied how seismic forces are transmitted to vertical and horizontal components using advanced numerical approaches (Dujič & Žarnić, 2006; Toratti, 2001). Several studies also highlighted the effect of thermal insulation on seismic behaviour. The behaviour of structural insulation panels, composite walls, and passive insulation was analysed from the point of view of seismic resistance (Donovan & Memari, 2015; Heiduschke et al., 2006). Experimental and numerical studies further confirmed the role of insulation type in stiffness and damping (Szczepanski et al., 2015; Szczepański et al., 2019). Apart from the aspects of thermal insulation and wooden panels in global terms, it turns out that structural connectors and their proper selection have an extremely significant impact on the behaviour and the response of wooden structural elements under dynamic load. Moreover, the rigidity of joints and their strength are basic issues in the design of structures (Branco et al., 2011; Santana & Mascia, 2006), and the influence of the geometry of connected structural elements on the rigidity of joints has already been confirmed (Malesza, 2017).

The variety of connectors gives researchers a lot of room for manoeuvre in the field of research. Joints with notches, dowels, glued or toothed joints are just a part of possible connections applied in the case of wooden skeleton technology (Branco et al., 2011; Debertolis et al., 2025; Gao et al., 2023; Gresve et al., 2025; Palma et al., 2010; Seim et al., 2022; Suzuki et al., 2025; Verbist et al., 2017; Yin et al., 2025). The use of nails and screws is considered the oldest and most commonly used approach. Elements in almost every wooden construction system also affect the behaviour of structures under dynamic loading. However, while numerous studies have focused on the local pull-out or shear strength of individual fasteners, there is a comparative lack of experimental data quantifying the influence of these common fasteners on the global dynamic response—specifically stiffness, damping, and failure mechanisms—of full-scale, complete wall frame assemblies subjected to simulated seismic loading. This study aims to fill that gap by providing a direct, controlled comparison between nominally identical frames differing only in their primary connection type (nails vs. screws).

Hence, the objective of this article is to study the effect of two different types of connections on the dynamic response of wooden frames, namely, nails and screws as typical fasteners. The primary research hypothesis is that replacing nails with screws in typical frame connections will significantly enhance the global dynamic performance of a wooden wall frame, measured through increased stiffness, modified damping, and a shift in the failure mode from the frame joints to the foundation connection. The key research objective concerns the quantitative difference in dynamic stiffness and damping between nailed and screwed frames, the difference in the failure modes under progressive dynamic loading, and the practical implications for seismic design. Experimental tests have been conducted on two different wooden frames. The first one is connected with nails, while the second one is connected with screws. Standard wall frame panels were subjected to harmonic loading at multiple frequencies and displacement amplitudes. The study was focused on the behaviour of wooden frames in the horizontal plane, so as to determine their dynamic characteristics from the point of view of the influence of fasteners on the structural rigidity and damping. Wooden frame elements were prepared by applying the utilitarian technology currently used by the company involved in prefabricated wooden construction.

Materials and Methods

1. Experimental Setup

A specially designed experimental setup (Figs. 1 and 2) was applied during the tests. The main frame of the stand, with external dimensions of 3000×500 mm, was constructed using steel beams with an IPE240 cross-section, and it was fixed to the floor slab. For installation of the wall frame panels, the additional mounting socket, made of steel elements with dimensions of 1500×600 mm, was welded to the main frame (Fig. 3). The Parker ETB125 dynamic actuator was fitted to the rig (Fig. 3), with specifications: maximum force 45 kN, displacement range ±25 cm, and peak acceleration 10 m/s^2 (Jaroszewicz et al., 2016). These parameters allowed dynamic and destructive testing of the wall frames.

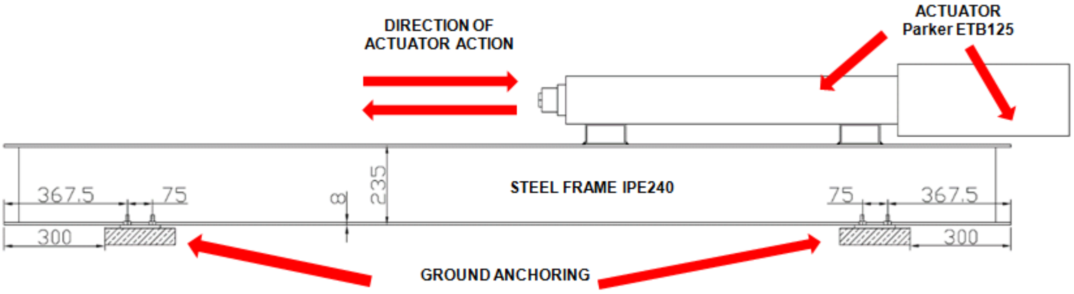

Fig. 1. Sketch of the experimental setup – side view (mm)

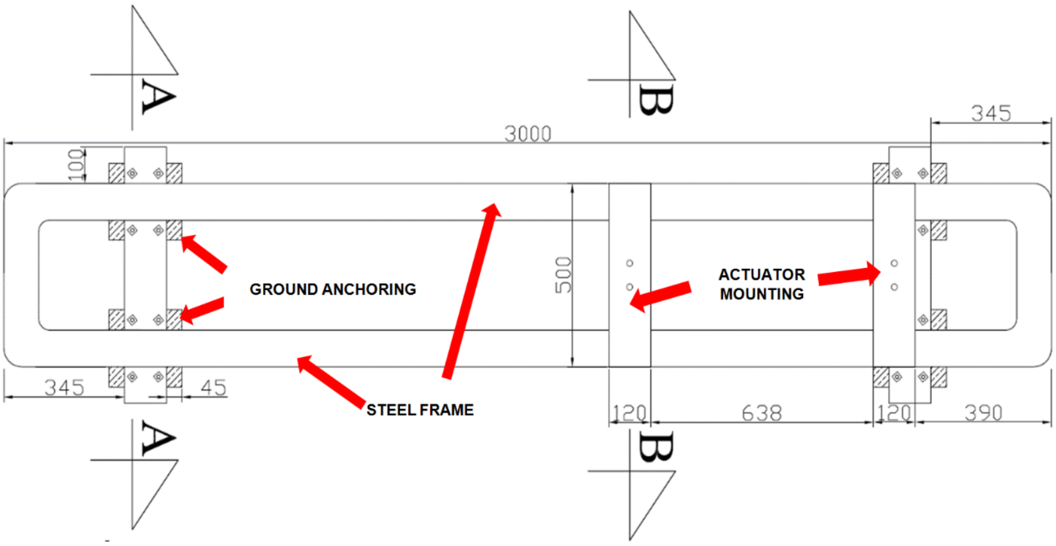

Fig. 2. Sketch of the experimental setup – top view (mm)

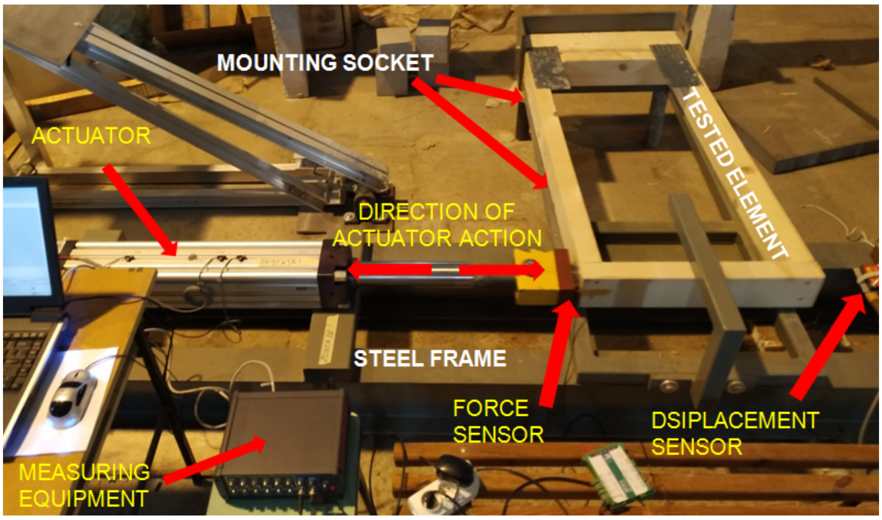

Fig. 3. Experimental setup with wooden frame element

Measurements were taken with the Alitec VIMEA VE 16BCA system at a sampling frequency of 500 kHz. A KMM40 force sensor (range: 50 kN, sampling frequency 200 Hz) recorded applied forces. A sensor at the actuator shaft measured displacement, while a laser device (optoNCDT1302, ±100 mm range, 750 Hz) captured overall movement. Testing consisted of harmonic actuator motions, with the rod permanently fixed to the specimen at the force sensor location (Fig. 3).

2. Tested Elements and Material Characterization

Two models of wooden structural frames were used for dynamic testing. The models had the same typical external dimensions of 60×114 cm, while different types of connectors were used. This study was designed as a focused comparative analysis between two representative full-scale wall frame assemblies (n=number of samples=1 for each fastener type), where each specimen was subjected to an extensive regimen of 25 harmonic loading tests followed by a destructive test. While this approach provides robust, internally consistent data for direct comparison of system-level performance, it is acknowledged that conclusions regarding statistical significance across populations would require future work with larger sample sizes. The tested elements were made of solid structural softwood classified as C24 according to PN-EN 338. The wood species was spruce (*Picea abies* (L.) Karst.), identified in accordance with PN-EN 13556, which is the most commonly used species in industrial prefabricated timber-frame construction in Central and Northern Europe. The arrangement of annual growth rings in the cross-sections corresponded to flat-sawn timber, with rings predominantly lying parallel to the wider face of the cross-section. This reflects standard industrial practice and ensures uniformity across all tested specimens. The moisture content of the timber was controlled prior to testing and corresponded to service class 1 conditions. The average moisture content was 12 ± 1%, measured using a calibrated resistance-type moisture meter in accordance with PN-EN 13183-2, with measurements taken at multiple locations along each element. The wood density was determined based on mass and volume measurements of representative samples taken from the same batch of timber. The mean density was $\rho = 420$ kg/m^3, with a coefficient of variation of approximately 8%, which is typical for spruce timber in strength class C24 and consistent with values reported in the literature. All tested members complied with the visual and strength grading requirements of class C24. Natural features permitted by the standard, such as knots, local slope of grain, and minor machining inaccuracies, were present within allowable limits. No elements containing defects exceeding the limits of C24 (such as excessive wanes, shakes, resin pockets, or unacceptable warping: bow, spring, cup or twist) were included in the test specimens. Special attention was paid to maintaining an appropriate minimum distance between knots and critical

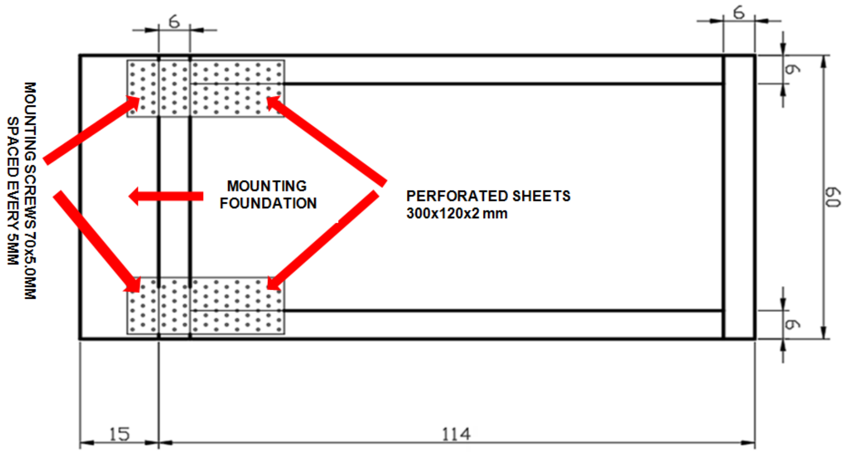

Fig. 4. Sketch of the tested element (cm)

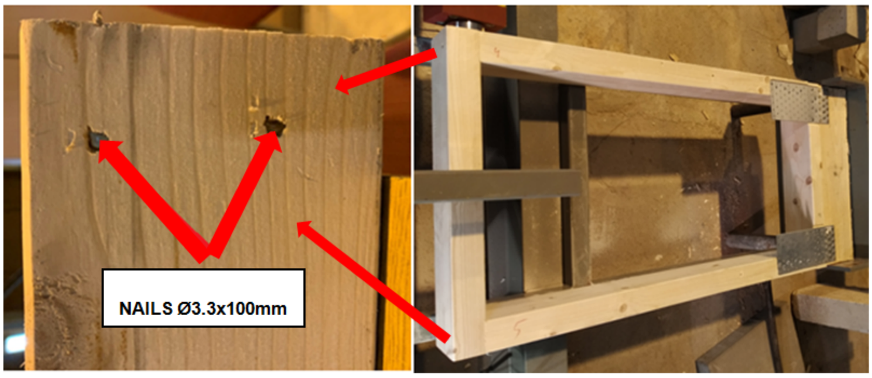

Fig. 5. Element with nailed connections (connection of the posts with the cap)

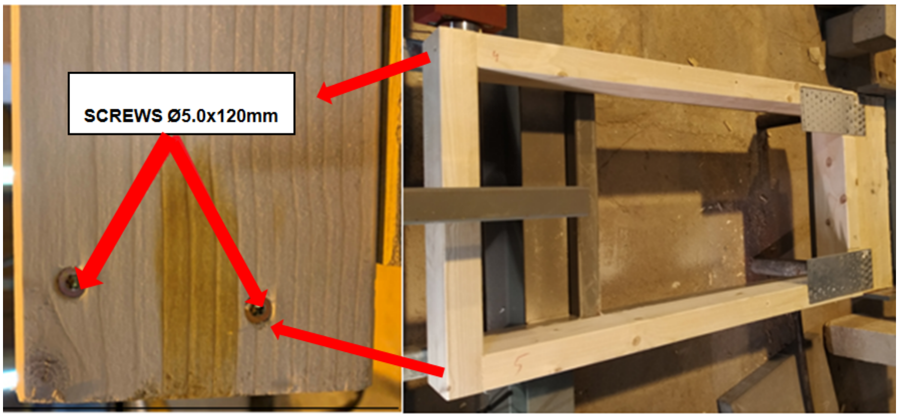

Fig. 6. Element with screwed connections (connection of the posts with the cap)

structural zones, particularly near the joints of the frame elements. Areas adjacent to connections (post-cap joints and post-foundation anchorage zones) were free from large knots or defect concentrations, ensuring that the observed behaviour resulted from the mechanical performance of the connections rather than premature material failure. Posts with a cross-section of 60×120 mm made of C24 wood were applied in both cases. A 2 mm-thick perforated sheet with dimensions of 120×300 mm was used for connecting the ground beam with the posts (Fig. 4), similarly as in the case of real structures. Mounting screws 15×70×5.0 mm, spaced every 5mm, were applied for anchoring. In both cases, KMWHT 5.0×70 mm screws were used to connect the frame structure to the foundation. 15 screws were applied for each perforated sheet (see Figs. 3 and 4 for their locations). The construction of the first tested element consisted of posts connected to the cap beam using two nails Ø3.3 mm with a length of 100 mm, as in the typical technology (see Fig. 5). The design of the second tested element consisted of posts connected to the cap beam using two screws Ø5 mm with a length of 120 mm, as in the standard technology (see Fig. 6).

3. Tests procedure

During the experimental tests (see Fig. 7), both models were subjected to harmonic excitations. Several measurements were carried out on each of the two wall panels, which eliminated the possibility of misinterpretation of the results obtained. Each frequency level (0.5, 1.0, 1.5, 2.0, 3.0 Hz) was combined with displacement amplitudes (10, 20, 30, 40, 50 mm). Each frequency was tested five times with all five displacement amplitudes (i.e., the 0.5 Hz was tested for amplitudes 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm, and so on for the other frequencies). Consequently, the experiments were performed 25 times (5 frequencies with 5 amplitudes each). The measurement time for individual tests was equal to 20 seconds. In order to eliminate the fatigue effect of the element in the initial phase of the test, the frequency for constant amplitude was changed, starting from 10 mm. In the last stage of the test, the maximum destructive force was measured.

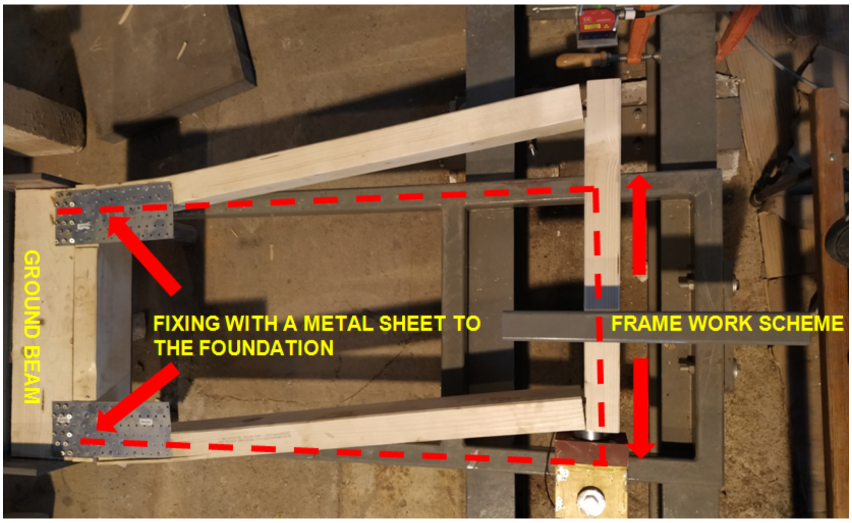

Fig. 7. Scheme of the tests

Results and Discussions

Both models of frames were mounted alternately on the test setup and tested in accordance with the adopted procedure. Representative hysteresis loops were derived, from which damping ratio (ξ), stiffness (*K*), and strain energy (*W*) were evaluated according to the formulas (see also Fig. 8) (Falborski & Jankowski, 2017, 2018):

$$\xi = \frac{\Delta W}{2\pi \cdot F(x_e) \cdot x_e} \tag{1}$$

$$K = \frac{F(x_e) - F(-x_e)}{2 \cdot x_e} \tag{2}$$

$$W = F(x_e) \cdot x_e \tag{3}$$

where $F(x_e)$ is the lateral force at displacement x_e, ΔW is the energy dissipated in each cycle, which is an area enclosed by the hysteresis loop.

1. Dynamic Performance and Failure Analysis of the Nailed Frame

In the first stage of the investigation, the nailed wooden frame was installed on the stand. The representative example of the results of the study in the form of the hysteresis loop is shown in Fig. 9. Mean stiffness and damping ratio values are summarised in Table 1. It should be added that in the initial phase of the tests, at the frequency of 0.5 Hz and displacement amplitude of 30 mm, the first adverse effects of dynamic load were observed in the form of a crack in the foundation at the edge in the line of mounting screws. The crack was significantly increased at a frequency of 2 Hz and an amplitude of 10 mm. Then, at 3 Hz and 20 mm amplitude, significant backlash was observed in the corners of the frame at the connection between the posts and the cap (Figs. 10 and 11). The test ceased to be authoritative for a 50 mm displacement amplitude. Then, significant cracks appeared in the foundation, and bending of the assembly plate took place, which, in consequence, led to the destruction of the element.

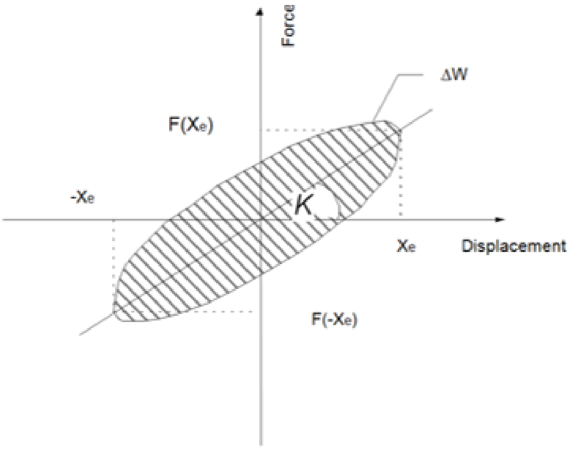

Fig. 8. Hysteresis loop

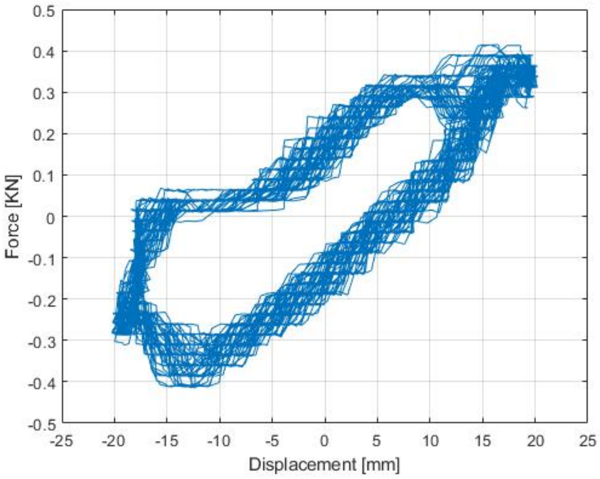

Fig. 9. Hysteresis loops for the nailed wooden frame – 3 Hz and 20 mm

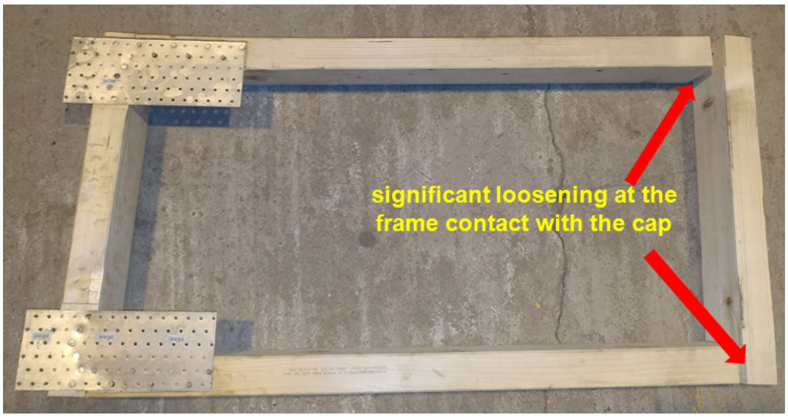

Fig. 10. Element with nailed connections after the study (general view)

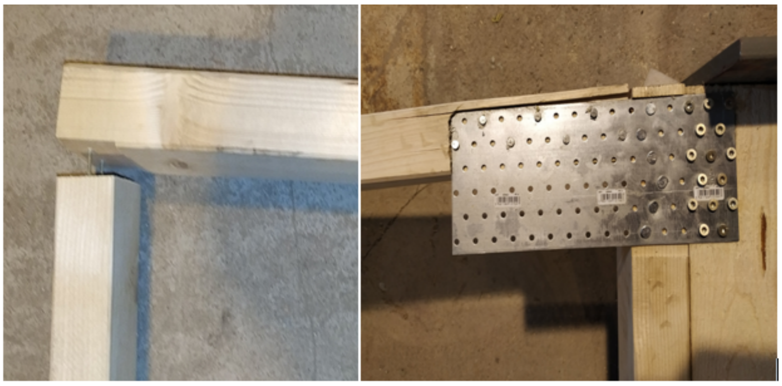

Fig. 11. Element with nailed connections after the study (view of cap and foundation connection)

Table 1. Values of stiffness and damping ratio for the nailed wooden frame

Frequency [Hz]	**Stiffness** [kN/m]	**Damping ratio** [%]
3.0	15.65	20.39

2. Dynamic Performance and Failure Analysis of the Screwed Frame

The screwed frame was tested following the same procedure. A representative hysteresis loop is shown in Fig. 12, with average stiffness and damping in Table 2. Early signs of looseness were first seen at 2 Hz and 20 mm, but did not impair testing. Additional runs were performed at 1 Hz with amplitudes of 60 and 80 mm. At 60 mm, cracks appeared along a post near the fixing plate (Figs. 13, 14). At 80 mm amplitude, tests ended due to equipment limits. The screwed frame withstood all experiments without experiencing notable damage.

3. Comparative Discussion

The dynamic behaviour of wall panels with nailed and screwed joints was studied experimentally. Both were subjected to harmonic excitation at varying frequencies and amplitudes. Stiffness and damping were calculated from hysteresis loops.

- Although nails and screws were applied at identical locations, the structural responses differed substantially. The observed nonlinear hysteresis and pinching effects are characteristic of timber and its connections (Sandoli et al., 2021; Tomei et al., 2023), and were influenced by the specific material characteristics described in Section 2.2, such as wood density and the presence of permissible knots.
- Compared with nailed joints, screwed connections considerably improve the stiffness of wooden frames, with a maximum increase of 51.1%. This substantial increase aligns with the expectation due to the larger diameter and superior withdrawal resistance of screws, and its magnitude is of clear practical significance for seismic design, where increased stiffness can reduce inter-story drifts.

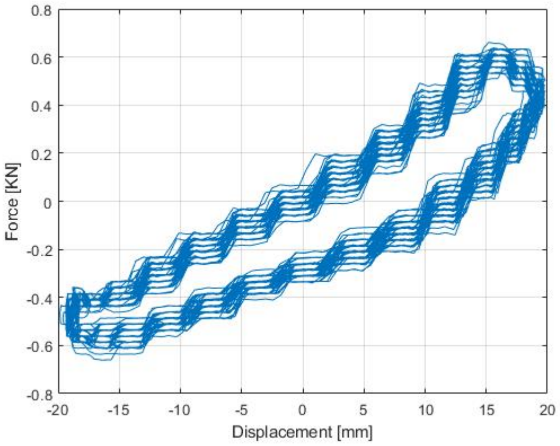

Fig. 12. Hysteresis loops for the screwed wooden frame – 3 Hz and 20 mm

Fig. 13. Element with screwed connection after the study (general view)

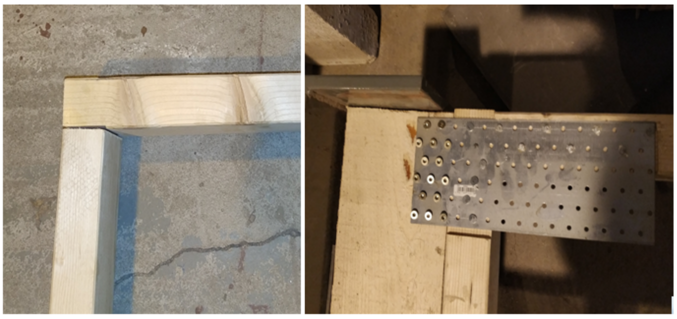

Fig. 14. Element with screwed connection after the study (view of cap and foundation connection)

Table 2. Values of stiffness and damping ratio for the screwed wooden frame

Frequency [Hz]	**Stiffness** [kN/m]	**Damping ratio** [%]
3.0	23.65	21.94

- Differences in damping were smaller, up to 7.6%, due to friction effects in both cases. This smaller variation suggests that, within this configuration, the energy dissipation mechanism is dominated by wood friction and deformation at the joint interfaces, which is less sensitive to the fastener type than the stiffness.
- The screwed frame endured all tests without critical damage, while the nailed frame failed under higher demands. This indicates a clear shift in the governing failure mode. The failure progression in the nailed frame—from joint backlash to foundation failure—suggests that nails, with their lower

rotational restraint, transfer dynamic moments unfavourably to the post-cap zone and subsequently to the foundation anchorage. In contrast, the stiffer screw connections effectively transferred shear but induced higher localized stresses at the wood-screw interface near the foundation, leading to wood cracking rather than joint failure. This finding is consistent with the principle of designing for predictable, ductile failure in seismic zones.

- Screwed joints reduce stress concentration at the foundation interface, while nailed joints transfer stresses unfavourably to post-cap zones. The practical implication is that screws engage the foundation connection more directly, where engineered anchors (as used here) typically have higher safety margins, whereas nails necessitate closer scrutiny of the post-to-beam joint detail.
- In both cases, the observed response was nonlinear, reflecting the inherent behaviour of timber.

Therefore, screws are recommended over nails to enhance the seismic resilience of timber wall frames exposed to dynamic hazards. This strengthening approach is low-cost and can be implemented during design and construction. Notably, screws transfer stresses to the foundation connection, where various anchoring solutions provide greater safety margins, whereas nails concentrate stresses in less favourable post-cap regions.

Future research will explore different fastener types, arrangements, and quantities to further clarify their effect on the seismic response of timber wall panels. A key direction will be to conduct tests with multiple replicates to allow for rigorous statistical analysis of the observed differences and to account for the natural variability of wood material properties.

Conclusions

This experimental study provided a direct comparison of the dynamic response of wooden wall frames connected with nails versus screws. The results confirm the primary hypothesis that screwed connections offer superior performance. The main findings of the study are listed as follows:

1. Screwed connections increased the global lateral stiffness of the frame by up to 51.1% compared to nailed connections.
2. The damping ratio was less sensitive to the fastener type, showing a maximum difference of 7.6%.
3. The failure mode shifted significantly: nailed frames failed due to joint play and subsequent foundation overload, while screwed frames demonstrated a more robust performance, with the failure initiating in the wood member near the stiff connection.
   The study underscores that the choice of common fasteners has a profound impact on the global seismic behaviour of timber frames. Specifying screws over nails is a simple, cost-effective measure to enhance stiffness and promote a more favourable failure mechanism, contributing to improved seismic resilience in light-frame wood construction.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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