WOOD RESEARCH doi.org/10.37763/wr.1336-4561/67.2.291301
e-ISSN 2729-8906
67(2): 2022 291-301 pp.

DESIGN AND PERFORMANCE OF NAIL CONNECTION IN WOOD FRAMING SHEAR WALLS

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(RECEIVED NOVEMBER 2021)

ABSTRACT

As the preferable lateral resistance system of a wood shear wall is attributed to the good lateral performance of nail connection, this paper aims at investigating the pull-out and shear performances of framing members' nail connection in wood shear walls under monotonic loading. It was found that the main failure mode of the pull-out behavior of nail connection was the withdrawal of threaded nails from framing members. In addition, the shear behavior of nail connection was characterized by plastic hinge of threaded nails, local tear of spruce-pine-fir (SPF) on the top of nails, and nail caps that were obliquely embedded into the surface of SPF. The average ultimate load and displacement of shear mode were 1.48 times and 5.12 times higher than those of pull-out mode, respectively. According to the research results, the corresponding exponential numerical model was established, which provided basic data for the lateral performance research and finite element simulation analysis of wood shear walls nail connection.

KEYWORDS: Framing members, threaded nail, pull-out, shear, exponential model.

INTRODUCTION

In low-rise wood-frame structures subjected to earthquake loading, shear walls are commonly used as the primary component of the lateral load resisting system (Folz and Filiatrault 2001). Under such loading, the failure of shear walls generally occurs at nail connection. Especially for the wall corner of light wood frame construction without anchor bolt, under lateral loading, such as earthquake or wind, the studs near the end of the wall will have obvious pull-up phenomenon, and the studs will also have relative horizontal dislocation with the top and bottom plates (Mingbin 2019, Pan et al. 2009). Therefore, the pull-out and shear behavior of the nail connection of light wood frame construction framing members (connection between the studs and the bottom and top plates) is important for the lateral performance and finite element simulation analysis of wood shear walls. For a long time, researchers have focused on the shear performance of the nail connections between sheathing and framing members, but less on the nail connections between framing members. Li (2009) studied the influence of mortise and tenon joint structure and nail connection of structural sheathing on the lateral resistance of wood shear walls. It was found that the main failure modes of the nail connection were nail withdrawal and broken nails; the mortise and tenon joint structure was more likely to be damaged than nail connection. Leichti (2006) studied the shear behavior of nail connection between structural sheathing and framing members with different thickness. It was found that the thinner the structural sheathing, the easier the nails were punched through structural sheathing surface. Additionally, the thicker structural sheathing resulted in nails more easily broken or sheared. In a study on nail connection of wood shear wall, Xiong et al. (2011) studied the aspects of different structural sheathing thickness and nail edge-distance. It was found that the failure modes of nail connection were different with different thickness of structural sheathing, and the larger nail edge-distance, the easier the nails were damaged.

Du et al. (2012) studied the influence of wood grain direction on the nail connection performance of structural sheathing and studs. The results showed that structural sheathing had a great effect on the ultimate bearing capacity of nail connection, and nail connection in transverse wood grain can get larger ultimate bearing capacity. Zheng et al. (2015) studied the interrelation of many representative variables in wood shear walls, including sheathing thickness, nail edge-distance, and loading direction. It indicated that the failure modes of nail connection depended on sheathing thickness and nail edge-distance. The increase of nail edge-distance and sheathing thickness can greatly improve the ultimate strength and the ductility of nail connection. In a study on the nail connection performance in wood shear walls, in addition to the sheathing material, nail edge-distance and shear modes, different nail types, nails materials, and angles also have a great impact on the connection capacity, initial stiffness, and ductility, especially the tilted self-tapping screw connection (Que et al. 2014). Mi (2004) and Doudak et al. (2016) found that nail length, diameter, and surface threaded size had a great influence on the ultimate strength of the nail connection performance. This was found via the experimental test of the nail connection of wood framing members in three stress states of pull-out, shear, and rotation. The monotonic loading method was used to carry out the experimental study of the nail connection. The results showed that the lateral shear strengths of nail fasteners were mostly governed by failure modes, and the edge-distance of the fastener joints greatly influenced the strength. The results provided basic research data for the nail strength specification (Chen et al. 2008). In addition, the stiffness of the wood frame joints is improved by increasing the number of nails used to fasten the sheathings onto the framing members. The stiffness of the joints whose structure sheathings are glued onto the joists is equivalent to the control main-members joints (Wanyama et al. 2012, Riggio et al. 2015).

On the basis of the research results of many experts, an efficient numerical model to predict the load-displacement response and energy dissipation characteristics of wood shear walls under general quasi-static cyclic loading was introduced by Folz and Filiatrault (2001). According to the model, a constitutive model of nail connection for finite element analysis of wood shear wall was presented based on the nonlinear finite element theory. A few years later, Cheng (2007) and Liu (2013) conducted a series of experiments on the nail connection and obtained the bearing capacity numerical model of the nail connection under monotonic loading and quasi-static cyclic loading. The predicted load–displacement response and energy dissipation characteristics of the model agreed well with the nail connection test results of wood frame structures, making it possible to develop in future research structural models for more-complicated nail connection with good computational efficiency and accuracy.

MATERIAL AND METHODS

Materials and specifications of nail connection

A typical nail connection specimen was fabricated with two vertical spruce-pine-fir (SPF) connected by two nails. The SPF was imported from Paragon Solutions Inc, Vancouver, Canada, with an average moisture content of 12.8%, without defects, and was used as framing members, whose section size was 38 × 89 mm (Liu et al. 2019), No. 2 grade specification of SPF (Liu et al. 2018). Galvanized threaded nails of big cap with 4.02 mm diameter and 90 mm length were adopted to connect framing members (Gao et al. 2016). The nails were a high-quality carbon steel nails with surface quenching and galvanizing, they were produced by Shandong Oriental Cherry Hardware Group, Jining, China, whose average bending yield strength were 777.8 MPa. According to standard GB LY/T 2059 (2012), when the diameter of steel nails is 3.6 to 4.5 mm, the average bending yield strength should not be less than 620 MPa.

Design of nail connection specimens

According to the different stress modes of the nail connection, the nail connection specimens were divided into two groups: specimen A and specimen B, with 10 replicates for each group (ISO 16670: 2003). These two groups were used to simulate the pull-out and shear behavior of nail connection between the top plates or the bottom plates and the studs in wood shear walls. Two 90 mm galvanized threaded nails were used for specimen A to connect vertically, and the loading direction was parallel to the direction of galvanized threaded nails. The purpose was to study the pull-out performance of the nails when the studs were separated from the top or bottom plate. The two galvanized threaded nails were located in the middle of the specimen, and the distance between them was 50 mm, as shown in Fig. 1 (specimen A).

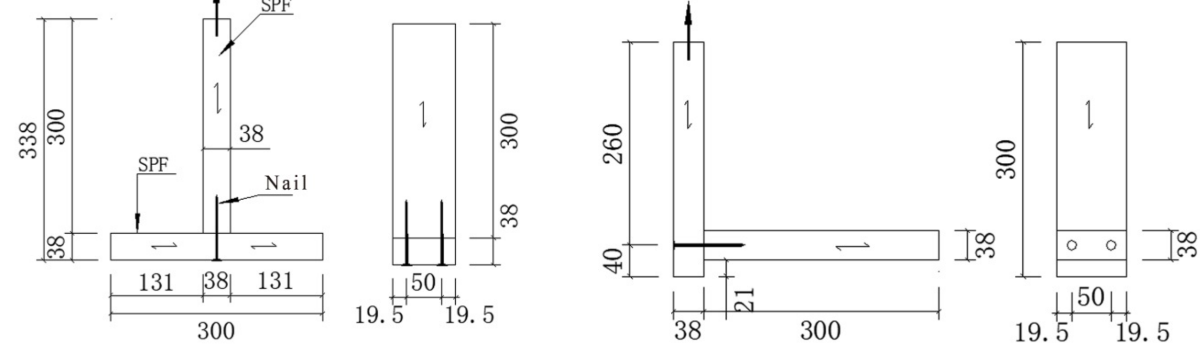

Fig. 1: Design of nail connection specimen A (left) and specimen B (right).

Two 90 mm galvanized threaded nails were used for specimen B to connect vertically, but the loading direction was perpendicular to the direction of galvanized threaded nails. The purpose was to study the shear behavior of the nails when the studs and the top or bottom plate moved laterally. The two galvanized threaded nails were located in the middle of the specimen, and the distance between them was 50 mm, the distance between the nails and the end of the vertical SPF was 40 mm, as shown in Fig. 1 (specimen B), which all refer to the Canadian Wood-Frame House Construction (Burrows 2005), Chinese GB 50005: 2003 and GB/T50361: 2005.

Methods

Fixtures were used to fix the framing members of the nail connection specimens on the universal electromechanical testing machine (Fig. 2). Ten specimens were tested under monotonic loading following ASTM D1761 (2006), with a loading rate of 2.54 $mm \cdot min^{-1}$. The load and displacement were recorded synchronously by force sensor and displacement sensor at a rate of 50 Hz. When the load dropped to 80% of the ultimate load or failed to reach 80% of the ultimate load (Micelli et al. 2010), but the specimen was seriously damaged, the test would be terminated immediately (Thomson et al. 2010).

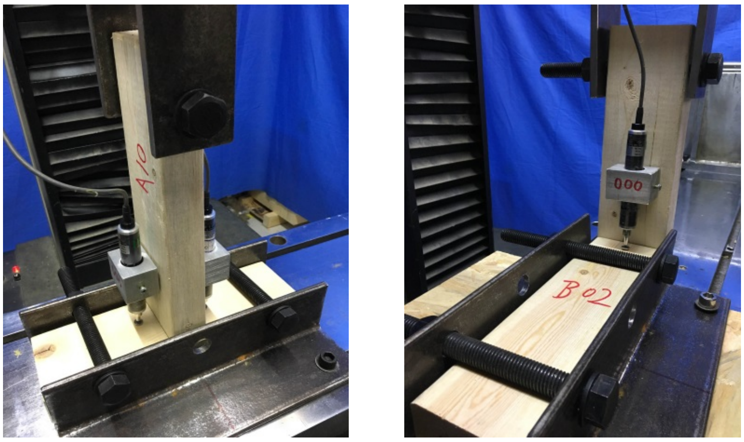

Fig. 2: Test setup of specimens.

RESULTS AND DISCUSSION

Failure modes

When the load of specimen A was less than $0.5 \cdot F_u$ (F_u is ultimate load), the load and displacement showed a linear variation. With the load increasing to more than $0.5 \cdot F_u$, the increase of the load was less than that of the displacement, and the load-displacement curve showed nonlinear variation. The nail caps were pressed into the surface of SPF. When the vertical load was greater than the friction between nails and wood fiber and the filament winding tension, screw thread of the nails cut off wood fiber around and created a gap between the horizontal and vertical members. When the load reached ultimate load F_u and continued to load until the load was reduced to $0.8 \cdot F_u$, the specimens were gradually damaged. The gap between the horizontal and vertical members reached 5 to 8.5 mm, and the nails were pulled out. Failure modes of the specimens are shown in Fig. 3, and the bearing capacity of the specimens decreased rapidly.

When the load of specimen B was less than $0.3\cdot F_u$, the displacement and load showed an approximate linear variation. When the load increased to a range of 0.3 to $0.8\cdot F_u$, the increase of the load was obviously less than that of the displacement, and the load-displacement curve was nonlinear. At this time, the wood fiber was cut or peeled off by the nails, the sound of wood tearing was emitted, the nail holes were enlarged, and the nails were slightly bent. When the load reached ultimate load, the tearing sound of wood fiber became larger and more brittle, and the slip between the two wood members increased continuously, and the upper gap became wider. The nails were further developed from shear modes to pull-out and shear modes. When the load reached the ultimate load and continued to load until the load was reduced to $0.8\cdot F_u$, the specimens were gradually damaged. The wood fiber splitting gap appeared at the end of the horizontally SPF, and the wood on the top of nails was strip-shaped torn along the end and slightly tilted upward. Failure modes of the specimens are shown in Fig. 3.

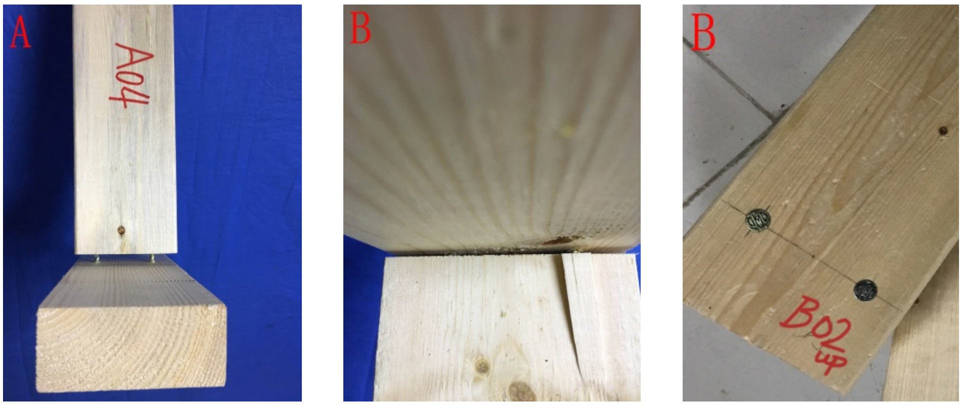

Fig. 3: Failure modes of specimens A (the nails were pulled out) and specimens B (the wood on the top of nails was strip-shaped torn and the nail caps were obliquely pressed into the vertical wood surface).

At this time, the nails had been yielding deformation and plastic hinge. The nail caps were obliquely pressed into the vertical wood surface, the lower edge of the nail caps was pressed a little deeper and cut off wood fiber, the load dropped sharply and lost the bearing capacity.

Analysis of the load-displacement curves

There was a large discreteness in the load-displacement curve of nail connection of specimens A and specimens B. The average load-displacement curve of the test results of 10 specimens have been used in this study. The curve was drawn by the average value of the load and displacement of 10 specimens in each group, as shown in Figs. 4 and 5.

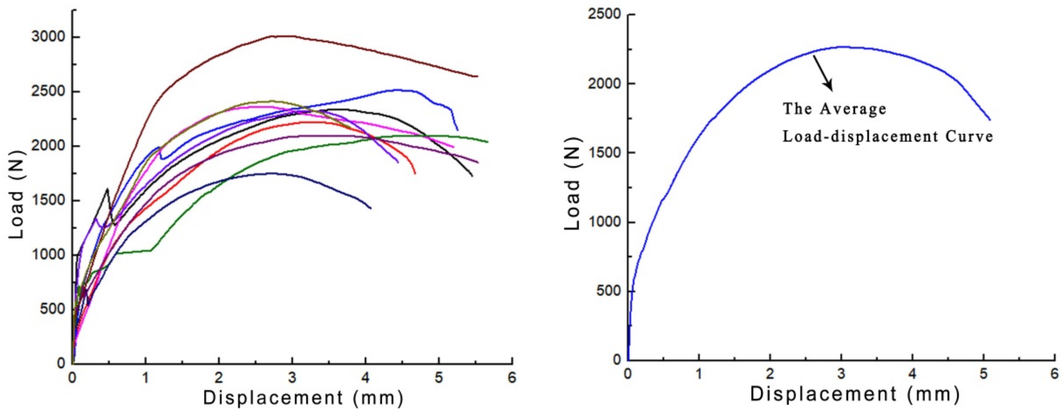

Fig. 4: The load-displacement curves of specimen A.

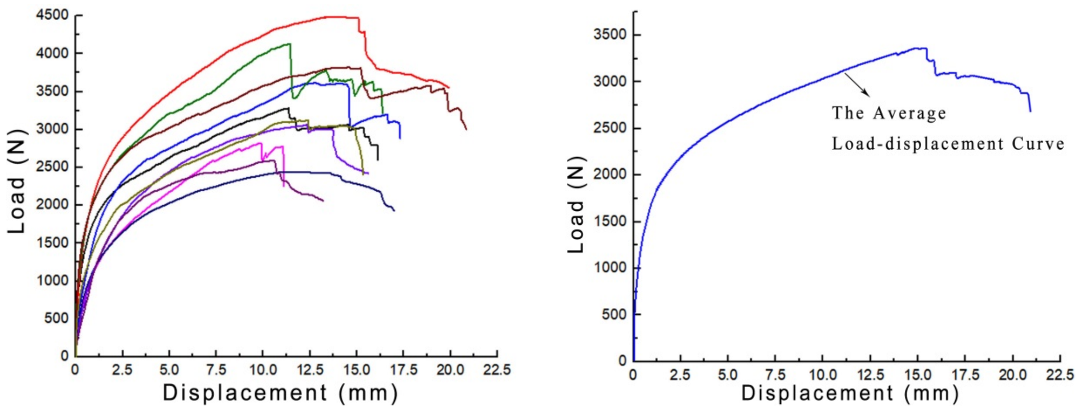

Fig. 5: The load-displacement curves of specimen B.

Discussion

The stress mechanism of shear and pull-out

As expected, the stress mechanism affects the strength (the ultimate load and yield load) and displacement of the nailed connections. Comparing the average load-displacement curves of specimens A and specimens B, the ultimate load of specimen A in pull-out mode reached 2267.89 N when the displacement was 3.03 mm, whereas the ultimate load of Specimen B in shear mode reached 3358.15 N when the displacement was 15.51 mm. The results indicated that the ultimate load and the ultimate displacement of specimen B in shear mode were greater than those of specimen A in pull-out mode because the stress mechanism of shear and pull-out of nail connection was different. Most of specimens B exhibit high ductility failure and undergo significant deformation before ultimate destruction (Guo et al. 2020). The pull-out bearing capacity of nails was mainly composed of the friction generated by the wedging and extrusion of wood fiber around the threaded nails, as well as the clamping force and the shearing force of cutting wood fiber between the threads of nails. The shear bearing capacity mainly depended on the composite shear and pull-out bearing capacity of the threaded nails to prevent the nails from bending and pulling out. Therefore, the shear bearing capacity of nails was greater than that of nail pull-out bearing capacity. The shearing mechanism of specimen B nail connection was basically the same as that of sheathing panels and studs in light wood frame construction.

The establishment of numerical model for nail connection pull-out

The framing members nail connection pull-out model of specimen A was based on the Foschi exponential skeleton curve (Fig. 6) and the Foschi exponential model (Eq. 1), and the fitting function curve was established by nonlinear least square fitting with MATLAB (MathWorks. Inc, U.S.A.):

$$F = \begin{cases} sgn(\delta) \cdot (F_0 + r_1 K_0 |\delta|) \cdot [1 - exp(-K_0 |\delta| / F_0)] & |\delta| \leq |\delta_u| \\ sgn(\delta) \cdot F_u + r_2 K_0 [\delta - sgn(\delta) \cdot \delta_u] & |\delta_u| < |\delta| \leq |\delta_F| \\ 0 & |\delta| > |\delta_F| \end{cases} \tag{1}$$

where: K_1, K_2, and K_3 represent the initial stiffness, the stiffness of the strengthened section, and the stiffness of the descending section, respectively, and F_0 is the intersection of the extension line of the strengthened section and the load axis. The fitting curve segment points are δ_u and F_u (δ_u is 3.17 mm and F_u is 2319 N). The δ_F is the failure displacement, corresponding to the displacement at $0.8 \cdot F_u$ in the descending section of the fitting curve, and its value is 5.19 mm. The other four parameters of the function were obtained by fitting according to the nonlinear least squares.

According to the average load-displacement curve of nail connection of specimens A, under pull-out stress, the nonlinear least square fitting was performed by MATLAB, and the load-displacement fitting curve parameters of specimen A when nail connection withdrawal were obtained (Tab. 1).

Tab. 1: Parameters of the nail withdrawal fitting curve.

F_0	K_1	K_2	K_3	δ_u	δ_F	F_u
1650.8	6156.1	210.6	-230.11	3.17	5.19	2319

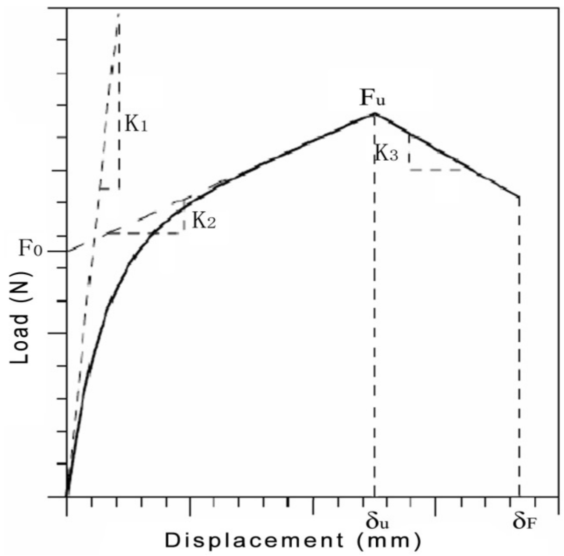

Fig. 6: Exponential load displacement curve.

In this study, the parameters of the nail withdrawal fitting curve of the framing members in Tab. 1 were brought into the Foschi exponential model (Eq. 1) to obtain the exponential numerical model (Eq. 2) in the nail withdrawal stress mode, described as follows:

$$F = \begin{cases} (1650.8 + 210.6\delta) \cdot [1 - exp(-6156.1\delta/1650.8)] & 0 < \delta \leq 3.17 \\ 2319 - 230.11 \cdot (\delta - 3.17) & 3.17 < \delta \leq 5.19 \\ 0 & \delta > 5.19 \end{cases} \quad (2)$$

The establishment of numerical model for nail connection shear

The framing members nail connection shear model of specimen B was based on the Foschi exponential skeleton curve model, and the fitting function curve was established by nonlinear least square fitting by MATLAB. The function expression was a piecewise function, δ_u is 15.57 mm, F_u is 3481.1 N, and δ_F is 20.06 mm. The other four model parameters of the function were obtained by fitting according to the nonlinear least squares. According to the average load-displacement curve of nail connection specimen B under shear stress, the nonlinear least square fitting was performed by MATLAB, and the load-displacement fitting curve parameters of nail connection specimen B were obtained, as shown in Tab. 2.

Tab. 2: Parameters of the nail shear fitting curve.

F_0	K_1	K_2	K_3	δ_u	δ_F	F_u
2211.7	4794.5	81.51	-155.2	15.57	20.06	3481.1

In this study, the parameters of the nail shear fitting curve of the framing members in Tab. 2 were brought into the Foschi exponential model (Eq. 1) to obtain the exponential numerical model (Eq. 3) in the nail shear stress mode, as presented by Eq. 3:

$$F = \begin{cases} (2211.7 + 81.51\delta) \cdot [1 - exp(-4794.5\delta/2211.7)] & 0 < \delta \leq 15.57 \\ 3481.1 - 155.2 \cdot (\delta - 15.57) & 15.57 < \delta \leq 20.06 \\ 0 & \delta > 20.06 \end{cases} \quad (3)$$

CONCLUSIONS

This paper presents an experimental study on the nail connection generally used in wood shear wall system. Two groups of nail connection with different stress modes were tested to failure in a monotonic way to investigate the failure modes, the ultimate strength, the ductility displacement, and the fitting empirical exponential model of the nail connection. Major conclusions can be drawn based on the above study and analysis as following:
(1) The load-displacement curve of framing members nail connection under monotonic loading is divided into four stages. The first stage is the elastic stage, where the load and displacement are small and change linearly, reflecting that wood fiber and nails are elastic change stages, and the slope of this curve is the initial stiffness K_1 of nail connection. The second stage is the elastic-plastic stage, and the curve shows obvious nonlinear characteristics, which shows that the connection between the nail and the surrounding wood fiber is loose under large load, and the

nonlinear characteristics are more obvious when it tends to yield. The third stage is the plastic stage. The nail hole expands and the nail surrounding wood fiber is further loosened. The nail completely yields. The displacement increase in this section is greatly more than the load increase. The slope of this section is the second stiffness K_2 of nail connection. The fourth stage is the failure stage. The onset of brittle failure events is overlap with some of the plastic and elastic displacements. The four steps can co-exist, especially when different points in a specimen are being considered together. With the increase of displacement, the load begins to decrease, and the slope of the line segment with the downward trend is the third stiffness K_3 of nail connection. *(2)* Under monotonic loading, the ultimate displacement and the ultimate load of threaded nails shear mode of framing members are greatly greater than those of withdrawal mode. *(3)* The main failure modes of the pull-out specimens are the galvanized threaded nail withdrawal from framing members. The main failure modes of the shear specimens are plastic hinge of threaded nails, local tear of SPF on the top of nails, and the nail caps are obliquely embedded into the surface of SPF. *(4)* In this paper, the fitting empirical exponential model established according to the nails shear and withdrawal test results can be effectively used to evaluate the load–displacement response of nail connections and the finite element simulation analysis of lateral resistance of wood shear walls under monotonic loading. If other structural materials and connectors are used, the model parameters need to be changed accordingly.

ACKNOWLEDGMENTS

The authors would like to acknowledge Research Start-up Fund for Introducing Talents of Anhui Polytechnic University (No. 2019YQQ022) and Research Projects of Anhui Polytechnic University (No. Xjky06201907) for providing funds for the first author to work on this project.

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