Application of small-diameter round timber as structural members in light frame construction

Guofang Wu\textsuperscript{a,}\textsuperscript{b}, Enchun Zhu\textsuperscript{c}, Haiqing Ren\textsuperscript{a,b}, Yong Zhong\textsuperscript{a} and Meng Gong\textsuperscript{d}

\textsuperscript{a}Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing, China; \textsuperscript{b}Research Institute of Forestry New Technology, Chinese Academy of Forestry, Beijing, China; \textsuperscript{c}School of Civil Engineering, Harbin Institute of Technology, Harbin, China; \textsuperscript{d}Wood Science and Technology Centre, University of New Brunswick, Fredericton, Canada

\section*{ABSTRACT}
Small-diameter round timber is a kind of by-product mainly from the thinning operation of the plantations. It is plentiful and inexpensive, and is generally destined for non-structural applications. The small-diameter round timber is rarely used as structural members. This study was aimed to provide an innovative but simple way to use the small-diameter round timber as structural members. Three kinds of composite members were developed to be used in light frame wood construction, i.e. the built-up studs, the wood-steel joists and the wood-steel roof trusses. The shearwalls and diaphragms made of the developed composite members were also examined. To facilitate the fabrication, the configurations of these members were described in details. Efforts were also made to investigate the structural performances of these members via full-scale tests. It was found that the developed composite members could be used as substitutes of dimension lumber in the framework of light frame construction. The developed members could be also pre-fabricated as standard components in a mill and assembled on site. As a result, application of small-diameter round timber as structural members developed would be an efficient way to increase use of forest resource from plantation and lower the construction cost of light frame buildings.

\section*{1. Introduction}

Forests, especially plantations, often contain a lot of small-diameter juvenile trees. Not only do these overstocked stands increase the risk of insect, disease, fire and drought damage, but they are also costly to manage (LeVan-Green and Livingston 2011). Parts of these trees are removed to make room for the growth of others in the process of thinning, producing a large quantity of small-diameter round timber every year. It is a kind of renewable and inexpensive natural resource, if used appropriately. The small-diameter round timber is mainly destined for non-structural applications such as pulp, board production or even fuels. To use the small-diameter round timber more effectively, some efforts have been made. Some researchers investigated the feasibility of using the small-diameter round timber as structural members (Wolfe 2000; Wolfe and Moseley 2000; Wang et al. 2002; Cumbo, Smith, and Cwii 2004; Wolfe and Murphy 2005). Chrisp, Cairns, and Gulland (2003) applied small-diameter round timber into the structural frame of a single-story residential centre. Fredriksson et al. (2015) used small-diameter round timber to fabricate cross-laminated timber panels by sawing the logs along the edge into tapered shape. However, the current research is still insufficient to provide effective ways to use small-diameter round timber as structural members. A simple, economical and efficient way of using this kind of forestry by-products is needed.

Light frame construction, widely used as residential buildings in North America, consists of wall, floor and roof assemblies. These components are assembled together to form a structure to achieve the desired function. In light frame construction, the dimension lumber studs, joists and trusses are the skeleton and the sheathing panels are the skin on the skeleton.

In this study, the conventional light frame construction was modified by utilizing small-diameter round timber to form the skeleton. A sketch of the modified structure is shown in Figure 1. Three kinds of composite members were developed, the built-up stud, the wood-steel joist and the wood-steel roof truss. Besides, the shearwalls made of the developed built-up studs and the diaphragms made of the developed wood-steel joists were also developed by replacing the framing members of conventional shearwalls and diaphragms.
2. Formation of the developed members and assemblies

2.1. The built-up stud

As shown in Figure 2, a built-up stud is comprised of two limbs of small-diameter round timber, which are fastened using U-shaped nails (Wu et al. 2018): A piece of small-diameter round timber is sawn into two halves to form two semi-circular limbs, or to form one bow-shaped limb if the size is small. The larger end of one limb is placed matching the smaller end of the other limb. Arranging limbs as above reduces the property differences between studs and makes the properties more uniform along the length of the stud. The U-shaped nails are applied to both sides of the limbs. The angle between the stud and the U-shaped nails is about 45 degrees. The crown of U-shaped nail used in this study had a length of about 160 mm and a diameter of 8 mm, and the leg of the U-shaped nail had a length of about 35 mm and a diameter of 3 ~ 4 mm. The built-up stud can be assembled with a jig so that every stud comes out the same width. The stud can be
manufactured in factory or on site and can be easily cut into the designed length.

2.2. The wood-steel joist

As shown in Figure 3, the developed wood-steel joist is a composite parallel chord truss. The top chord is made of small-diameter round timber, the bottom chord is either made of small-diameter round timber or steel rod. The web member is made of steel rod. The developed wood-steel joist is designed to have flooring material nailed or screwed to the top chord. The wood top chord is cut from small-diameter round timber that usually tapers, with a diameter of 60 mm or more at the smaller end. As shown in Figure 4, the top and bottom faces of the upper chord are sawn and surfaced to accommodate the floor plates above and the web members below. After sawing, the dimension of the chord is about 45 mm thick with a tapering width. The web members are actually a continuous steel rod bent into the designed zigzag shape. The bent yet continuous web member is welded to the

![Figure 3](image1.png)

*Figure 3.* Formation of the wood-steel joist.

![Figure 4](image2.png)

*Figure 4.* Processing the round timber into a wood chord.
2.3. The wood-steel roof truss

As shown in Figure 6, the developed wood-steel roof truss consists of two top-chord members made of the small-diameter round timber, a bottom chord made of steel tension rod, a vertical tension web member made of steel, and two diagonal web members made of the small-diameter round timber.

Figure 7 shows that the top chord is manufactured by sawing a small-diameter round timber into a bow-shaped cross-section. The flat top face of the chord provides a plane to connect with the roof decking or purlin. The smaller end of the timber is placed towards the ridge. The diagonal web member is manufactured with the timber by cutting it into appropriate length without dealing with the surface. To make sure that every truss comes out the same shape, full-sized setting out is required.

The details of all joints of a truss are shown in Figure 8. The details of the end joint are shown in Figure 8(a). It shows that the end of the round timber is cut into a flat bottom face, which is used to connect with the top plates of the supporting wall. Two vertical flat faces are made to fit the end into a section of steel channel. A hole is drilled through the end of the round timber and the steel channel. The steel bottom chord with a threaded end goes through the hole and is fixed with double nuts. The channel spreads the compressive...
stresses from the steel chord, which assists to prevent the timber from splitting.

The details of the ridge joint are shown in Figure 8(b). The joint is a kind of steel plate-clamped connection tightened with bolts. The end of each timber chord is cut to form a vertical plane, and then they are butted at the plane. A steel side plate is applied to each side of the joint and is tightened with four bolts. A vertical hole is drilled through the butted plane between the two timber chord members for the vertical steel web member to pass through. The end of the steel web is threaded for it to be fixed with double nuts. A thick enough steel pad is required to spread the compressive stresses.

The diagonal web member to the top-chord joint is a kind of framed joint. As shown in Figure 8(c), the top chord is notched with a flat face perpendicular to the web member, the web member contacts with the chord tightly. The joint is tightened with a staple at each side of the truss.

The central joint connects the vertical web, bottom tension chord and two diagonal webs together as shown in Figure 8(d). The two segments of the bottom chord meet in the middle and are spliced with two additional short steel bars welded along the side of the bottom chord. A gap is left between the two segments of the chord in a size just for the vertical web to go through. A piece of steel angle is placed to each side of the vertical web and is welded on top of the steel chord. This is to accommodate the diagonal web. The vertical web with a threaded end is anchored with double nuts below the chord. A thick steel pad between the nut and the bottom chord is also needed. A stiffening rib is welded in the middle of the angle and is inserted into a groove cut in the diagonal web. It
thus also prevents the diagonal web from sliding off the angle.

2.4. The shearwall made of the built-up stud

As shown in Figure 9, the shearwall consists of the bottom and top plates, studs and sheathing panels (Wu et al. 2015): Dimension lumber is adopted as the top and bottom plates for easier connection with the foundation or diaphragm than the irregular small-diameter round timber. Built-up studs are used as a substitute of the conventional dimension lumber studs. For the convenience of connection, dimension lumber studs may still be used as the end studs of shearwall. The built-up studs are connected to the top and bottom plates with nails. Toe nailing is not recommended due to the small size of a single limb of the built-up stud. The sheathing-to-frame nail connections are the same as in a conventional shearwall, in which nails are usually used for wood-based structural panels and screws are usually used for gypsum panels. Blockings are not used, because the configuration of a built-up stud makes it difficult to install the blockings within the frame of the shearwall.

2.5. The diaphragm with the developed wood-steel joist

As shown in Figure 10, the diaphragm consists of repetitive wood-steel joists at a prescribed space. Wood-based structural panels are attached to the top of the joists as the floor plates. The panels run in the direction perpendicular to the joists, the edges of which are placed on the developed wood-steel joists or on the rim or header joists around the perimeter of the diaphragm. Each panel shall be continuous over more than one span. Finish materials such as gypsum boards are applied to the bottom of the diaphragm where they serve as the ceiling for a room below.

Bracings are installed perpendicular to the joists within the framework. They are used to enhance the integrity and stiffness of the diaphragm and to reduce the deflection and vibrations via load sharing. Bracings are fixed to the bottom of the top chord of joist with nails. To increase the stiffness of the diaphragm, steel strips can be applied along the adjacent edges of the wood-based structural panels via screws or staples, as also introduced in an APA report (American Plywood Association 1997).

3. The structural performance of the developed members

To investigate the structural performance of the developed members, full-size specimens of the built-up studs, wood-steel joists, wood-steel roof trusses, shearwalls and diaphragms were manufactured with small-diameter round timber of larch trees growing in the northeast China, steel rods and connectors. The average diameter of the smaller end of the timber used in the test was 75.8 mm, with a coefficient of variation in the diameter of about 0.20. The average moisture content of the timber during test was 12%.

3.1. The built-up stud

12 specimens of the built-up stud were manufactured, as shown in Figure 11. Each wall-type specimen consisted of three built-up studs, which were partly sheathed with some OSB panels. 6 of these specimens were tested under axial compression and the other 6 were tested under eccentric compression. The load-bearing capacity was obtained and the failure modes observed. Under compression, the specimens of the built-up studs buckled out of plane. The buckling load of the stud developed under the axial load was nearly 91% that a 2 × 4 SPF stud with the same length and boundary conditions (Wu et al. 2018). This indicates
The failure mode of the wood-steel joist was either that the compression steel web members buckled or that the joint between the tension steel web members and the wood chord at either end of truss fractured under the applied load, as shown in Figure 13.

The load bearing capacity and flexural stiffness of the specimens are listed in Table 1. And by analysing the load–displacement curves, it was found that the bearing load of each test specimen was higher than 7.6kN when the deflection at mid span reached 1/360 of the span (Wu 2015), suggesting that the joist developed had sufficient strength and stiffness for the intended use.

3.3. The wood-steel roof truss

To investigate the structural performance, 6 wood-steel trusses with a span of 9 m and a height of 2.25 m were manufactured with small-diameter round timber and 14 mm-diameter steel rod for the bottom chord and the vertical web member. Similar to the test of the wood-steel joists, a specimen for testing is formed by linking two roof trusses with OSB strips, as shown in Figure 14. The specimens were loaded at the ridge joint and the diagonal web member to the top chord joint until failure.

It was observed that the small-diameter round timber between the ridge joint and the diagonal web member to the top chord joint buckled under the applied load, and finally fractured, as shown in Figure 15.

The load bearing capacity of the three pair of specimens were 33.94kN, 34.40kN and 22.04kN, respectively, with an average of 30.12kN and a standard deviation of 7.0kN. The load bearing capacity was equivalent to a line load of 3.35kN/m. Furthermore by analysing the load–displacement curves, it was found the vertical displacement was considerably small (Wu

Figure 11. Test arrangement of the built-up stud.

Figure 12. Test arrangement of the wood-steel joist.
Thus, the strength and stiffness sufficient to support the anticipated load with a maximum truss spacing of 610 mm.

3.4. The shearwall made of the built-up stud

To investigate the structural behaviour of the shearwalls, a total of 15 full-size 2.44 m x 2.44 mm shearwalls with different stud spacing, end studs and sheathing panels were manufactured and tested under cyclic lateral load, as shown in Figure 16. It was observed that the failure modes of the shearwalls with small-diameter round timber studs were similar to that of the conventional shearwalls, i.e. failure of the nail connections along the perimeter of the panels, without failure of the framing members being observed. The lateral resistance, stiffness and displacement capacity were evaluated and the results of this study showed that the developed shearwalls performed quite well under cyclic lateral load. For example, as for the shearwalls sheathed with OSB panels on one side only, the shear strength was 9.2 kN/m, which was about 3% higher than that of the conventional ones of the same OSB sheathing on one side (Wu et al. 2015). This suggests that the shearwall developed had sufficient lateral resistance for use in light frame construction.
found that the average in-plane shear stiffness $G A_s$ and flexural stiffness $E I$ of the diaphragms were 3862kN and $1.69 \times 10^{10}$kN-mm$^2$, respectively. So the stiffness of the developed diaphragms was lower than that of the traditional diaphragms (Wu 2015), thus, the effect of the stiffness of the diaphragm on the load sharing between shearwalls should be evaluated.

4. Conclusions

This study examined the feasibility of utilizing the small-diameter round logs as structural members for the light frame construction. Three kinds of structural composite members were developed, say built-up stud, wood-steel joist and wood-steel roof truss. In addition, the shearwalls with the built-up studs and the diaphragms with the wood-steel joists were also studied by replacing the conventional framing members with the studs and joists developed. All the members developed in this study were simple in configuration and could be easily manufactured. It was found that the developed composite members could be used as substitutes of dimension lumber in the framework of light frame construction. The members developed could be also pre-fabricated as standard components in a mill and assembled on site. As a result, application of small-diameter round logs as structural members could be an efficient way to increasing use of forest resource from plantation and lowering construction cost of light frame buildings.

To promote the application of the modified light frame construction, other behaviors, like the structural

**Figure 15.** The top chord of roof truss buckled and fractured.

**3.5. The diaphragm with the developed wood-steel joist**

The horizontal diaphragm plays a key role in the transmission of the lateral load to the vertical shearwalls. To investigate the effect of using the developed wood-steel joists in the framing on the structural performance of the diaphragm, 3 full size 4.88 m $\times$ 3.66 m diaphragms were manufactured and tested, as shown in Figure 17. It should be noted that only the top chord of the wood-steel joist instead of the whole joist was adopted as the framing members of the diaphragm in the test specimen. This was because the steel web contributes little to the in-plane stiffness of the diaphragm.

The stiffness of the diaphragm was obtained under non-destructive in-plane third point loading. It was

**Figure 16.** Test arrangement of the shearwall.
performance of the assembled framework, the vibration of the floor and the seismic capacity, are needed to be investigated further.

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Notes on contributors
Guofang Wu is an assistant professor, his research interests include wood mechanics and timber engineering, etc.

Enchun Zhu is a professor, he has worked in Cambridge University, Swinburne University and Brighton University. His engaged in the research of timber structure and thin wall structure, etc.

Haiqing Ren is a professor, her research interests include wood mechanics and grading of wood products, etc.

Yong Zong is an associate professor, his research interests include wood and bamboo products and timber engineering, etc.

Meng Gong is an associate professor. His current research interests include 3D printing technology and mobile/fixed tiny wood houses.

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