Lateral Load Performance of Panelized Wood I-Joist Floor Systems

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Abstract

Panelized light wood frame construction is becoming more popular due to the faster construction time and shortage of onsite skilled labor. To use light wood frame panels effectively in panelized floor systems, panel-to-panel joints must be fastened adequately to allow load transfer between panels. They must also possess in-plane shear strength and stiffness comparable to stick-built, staggered-sheathed assemblies. This study was designed to develop efficient and effective panel-to-panel joints for connecting adjacent floor panels built with wood I-joists and evaluate the efficiency of the joints in achieving diaphragm action. At first, a number of these panel-to-panel joints were tested in the laboratory using a small-scale diaphragm test setup to determine their efficiency in transferring in-plane forces between panels. Test results showed that a small decrease in in-plane stiffness was expected for the most effective joints, but their strengths were significantly higher than at the same location in a conventional site-built floor diaphragm. The presence of blockings and use of two-row nailing were found to considerably improve stiffness and strength. These features can be used to mitigate the potential reduction in mechanical performance of panelized floor construction, in comparison with the site-built wood I-joist floor.

Conventional stick-built wood-frame construction has continuously evolved to incorporate an increasing number of factory-built elements such as prefabricated wall, floor, and roof panels (Mantell et al. 2017, Said et al. 2017). The increased use of factory-built elements is a result of advancements made in manufacturing technologies, shortage of skilled on-site labor, and the demand for optimum solutions in wood construction (APA—The Engineered Wood Association 2016). Such panelized construction transforms conventional skeletal frameworks into panelized systems by assembling a building from discrete panels. The prefabrication and panelization allow part of the construction process to be performed under the controlled environment of a manufacturing plant, leading to a number of benefits, including faster, safer, and higher quality construction, and reduced construction waste. More recently, the panelized construction has been further fueled by the advent of the midrise wood construction market (Ni and Popovski 2015).

In the last two decades, panelized wall and floor systems have been developed and implemented in wood construction (Morse-Fortier 1995, Munoz-Toro et al. 2006, Davids et al. 2011, Martin and Gatto 2014). However, there are still technical challenges that need to be overcome if prefabricated floor panels are to achieve performance comparable or superior to conventional floors and the maximum cost saving in the construction process. Given the width restriction of these floor panels in transportation, the installation of a prefabricated panelized floor requires the connection of discrete floor panels on the job site. As a result, both flexural and in-plane resistance are affected. Therefore, it is a characteristic of panelized floor systems that in many instances joint performance is critical (Burnett and Rajendra 1973). To use panels effectively, panel-to-panel joints must perform adequately to promote load transfer between panels, prevent differential deflection under moving and point loads, and possess in-plane shear strength and stiffness comparable to site-built, staggered-sheathed assemblies (Morse-Fortier 1995). This article addresses the lateral load performance (i.e., in-plane stiffness and strength) of panelized floor systems.

Floors resist lateral loads exclusively through diaphragm action. The lateral load performance of a diaphragm relies on sheathing panels (grade, thickness, and layout), nailing patterns (size and spacing), provision of blocking, and width

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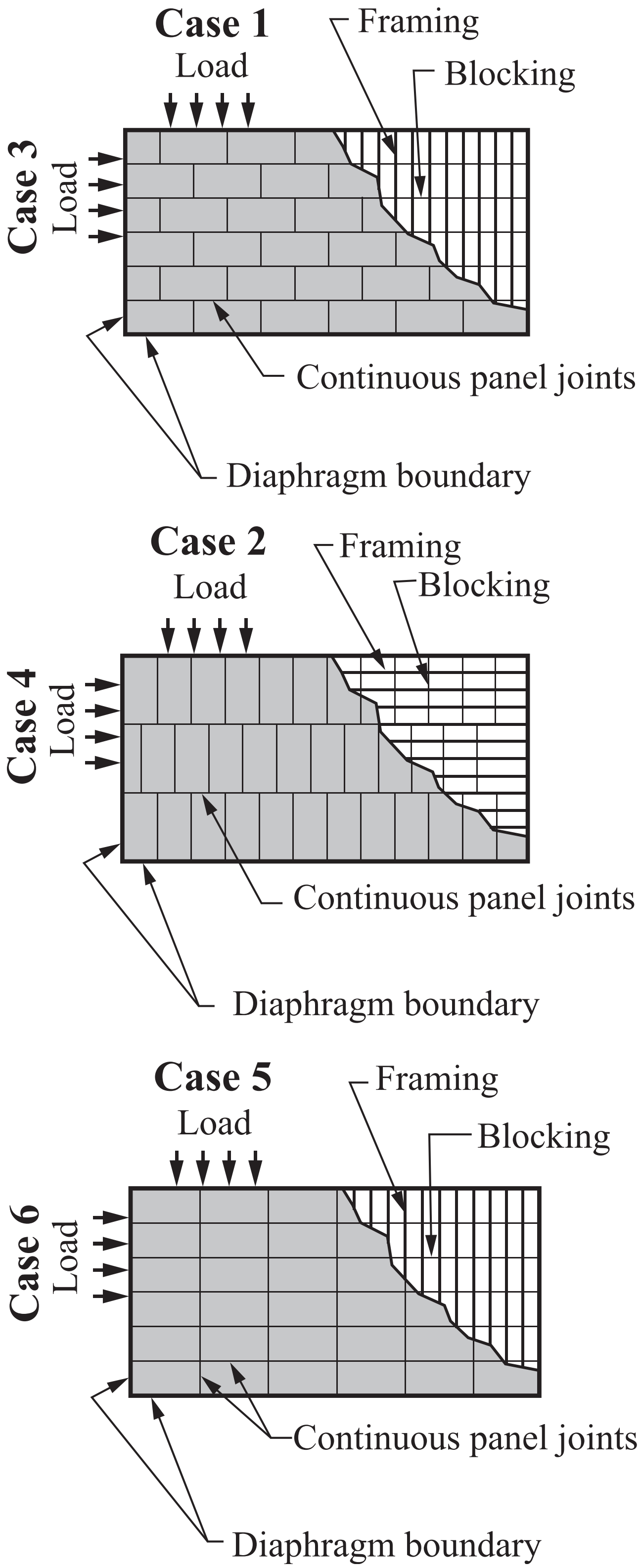

Figure 1.—Diaphragm cases (Canadian Standard Association [CSA] O86; see CSA 2019): (a) Case 1 and 3; (b) Case 2 and 4; and (c) Case 5 and 6.

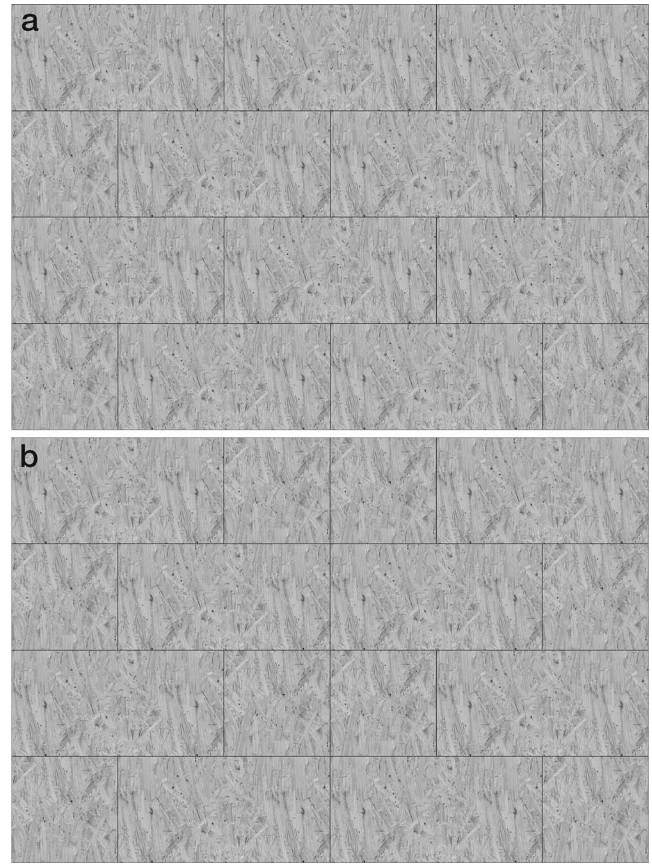

Figure 2.—Top view of panel configurations for Case 1: (a) conventional stick-built floor and (b) panelized floor.

of framing members (Stalnaker and Harris 1997, Yeh et al. 2016). In stick-built conventional floors, diaphragm action is significantly enhanced through staggered sheathing panels, blocked framing, force transfer through shared framing, and continuous chords at the perimeters (Morse-Fortier 1995). Panelized floors, however, disrupt the continuity of staggered sheathing in the middle of perimeter-chord development, and replace stiff sheathing-to-frame fastening by potentially more flexible frame-to-frame fastening. As a result, the ''interlocking'' effect in the staggered sheathing panels will disappear in panelized floor construction and diaphragm action may be impaired. On the other hand, extra nails need to be installed on panel-to-panel joints, which may enhance the diaphragm actions. For instance, the common requirement of nailing spaces for sheathing panels are 150 mm (6 in) on supported panel edges (i.e., perimeter edges of a panel) and 300 mm (12 in) on the intermediate supports. If the floor is built with prefabricated floor panels, the nailing pattern at the panel-to-panel joints will be two rows of nails spaced at 150 mm. In contrast, there is only one row of nails at 300-mm spacing at the same location in a conventional stick-built floor. Consequently, although the continuity of staggered sheathing panels is disrupted at the joints, the extra nails of panelized floors could offset the loss of the conventional interlocking effect. In addition, the added blockings at the joints for handling purposes could also provide some structural contributions. Therefore, the influences of these elements on diaphragm actions of panelized floor systems should be examined, which was the focus of this project.

The primary objectives herein are to demonstrate the lateral load performance of panelized floor diaphragms compared with conventional stick-built diaphragms and to

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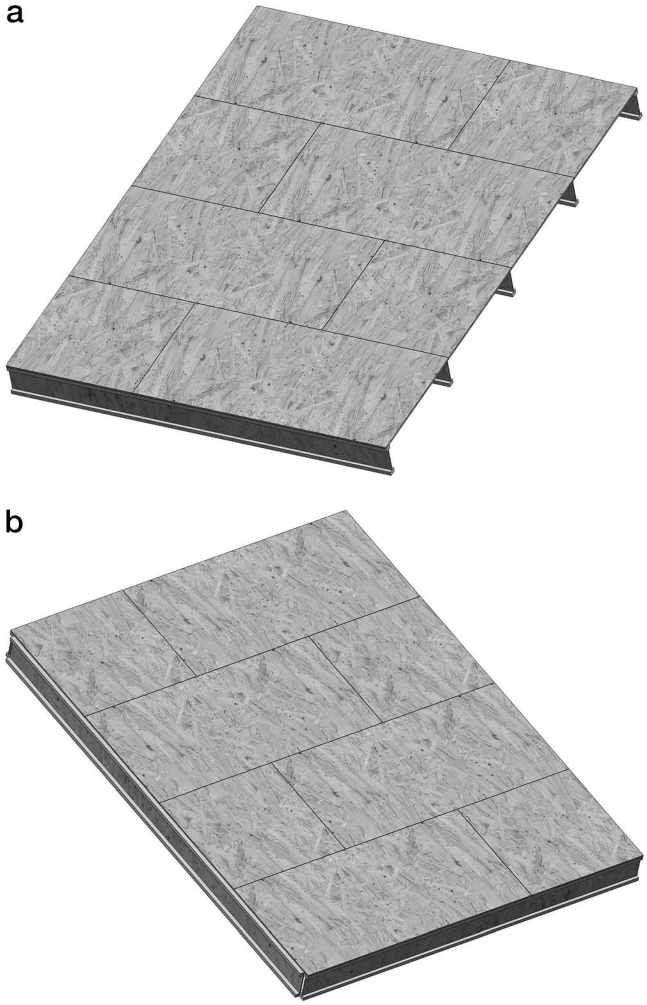

Figure 3.—Adjacent panels for prefabricated floor systems: (a) left panel and (b) right panel.

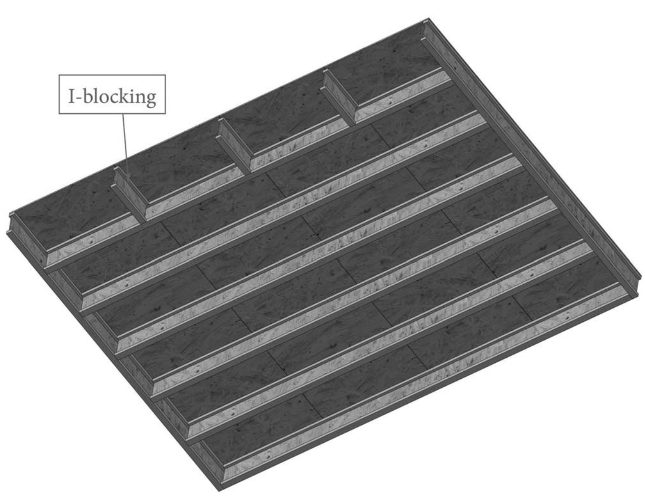

Figure 4.—Bottom view of left panel and installation of I-blockings.

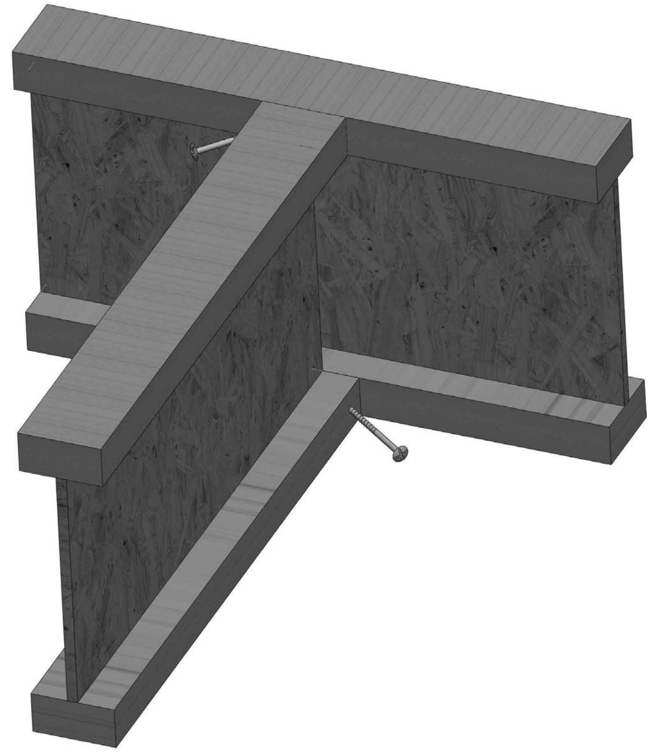

Figure 5.—Toe-nailed I-blocking.

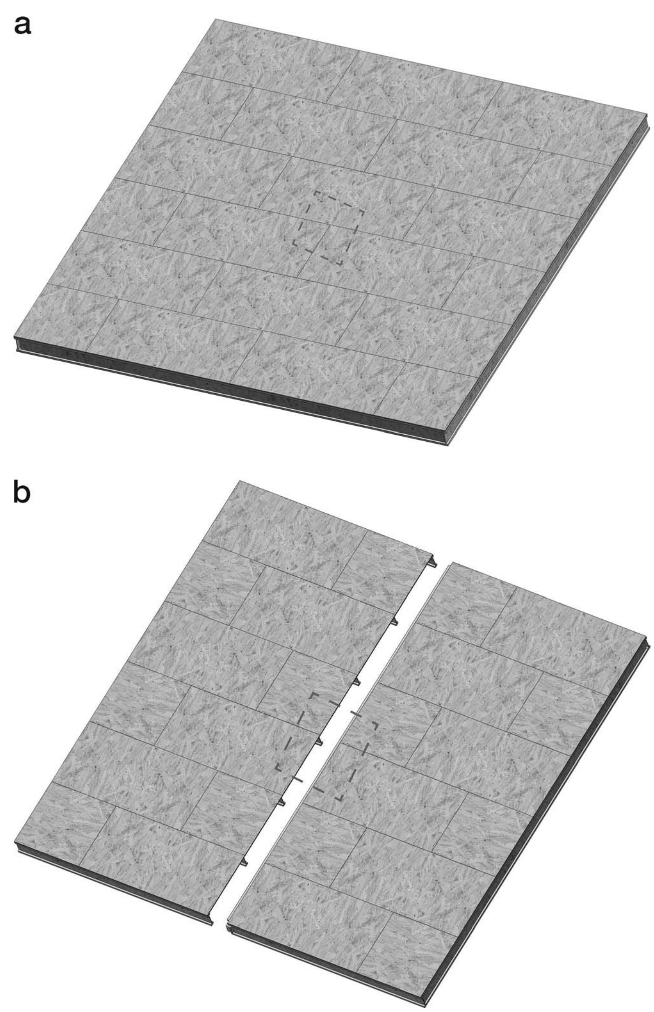

Figure 6.—Representative parts of conventional stick-built and panelized floor systems: (a) conventional and (b) panelized.

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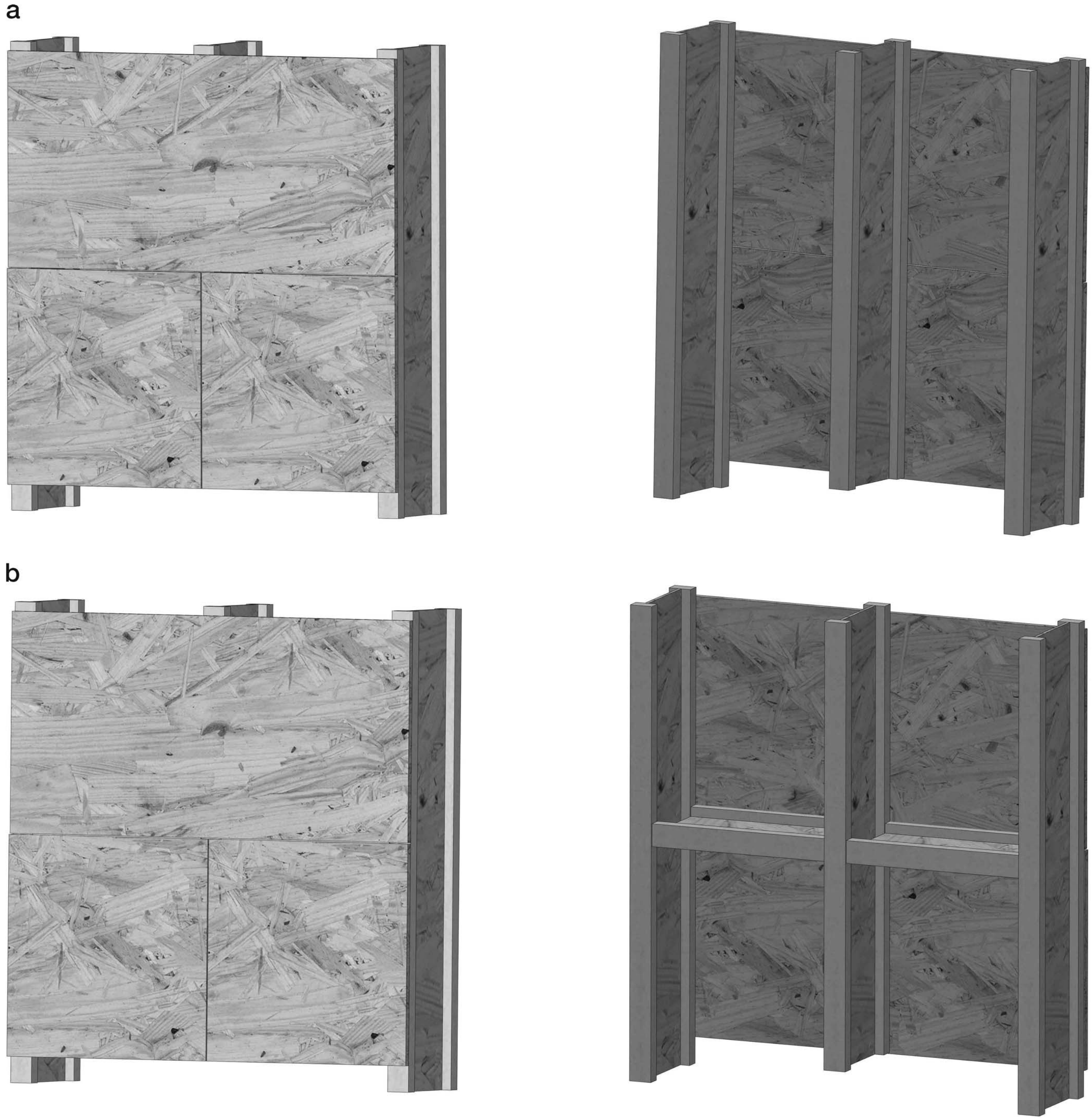

Figure 7.—Conventional specimen configurations (left: front view; right: back view). (a) Conventional specimens without blocking and (b) conventional specimens with blocking.

evaluate, in relative terms, the influences of interlocking effect by staggering sheathing panels, nailing patterns, provision of blockings, and flange width on the diaphragm action. At first, a prototype of prefabricated wood I-joist panel was developed for panelized wood I-joist floor systems. Only one joist with wider flanges is required at every interior panel-to-panel joint location. Then, an in-plane loading test was conducted on the panel-to-panel joints. The conventional diaphragm specimen was used as a reference. Test results are compared to evaluate if the diaphragm action of wood I-joist floors would be compromised in panelized construction compared with traditional stick-built construction.

Prototype of Prefabricated Wood I-Joist Panels

The prefabricated floor panels herein were constructed with engineered wood I-joists, which have been extensively used in light-frame wood diaphragms in North America for more than three decades (Yeh et al. 2016). Engineered wood I-joists are available in lengths of up to 20 m (66 ft) and can therefore be used to span over a few supports, thereby leading to further savings in construction time. Due to

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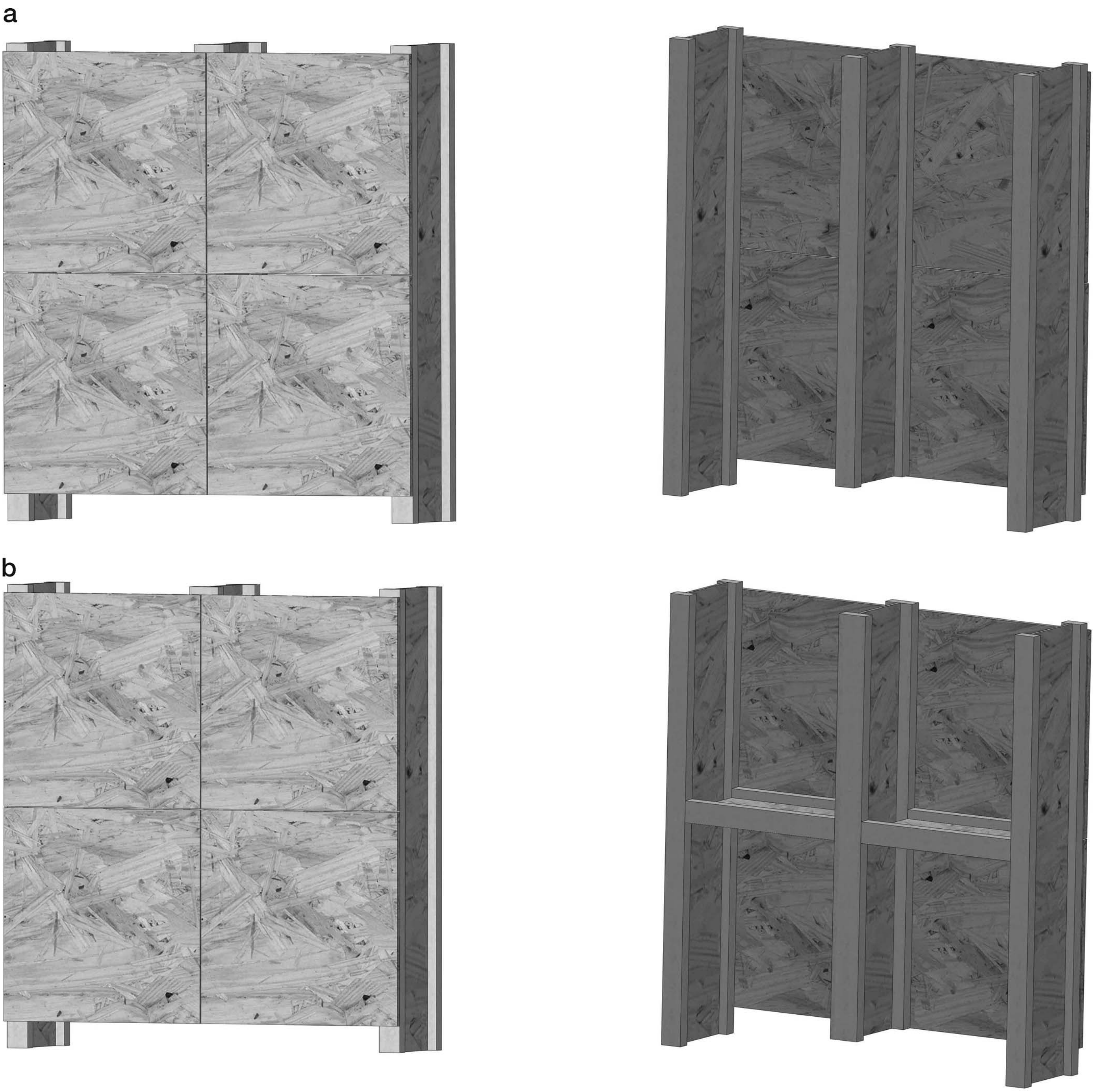

Figure 8.—Panelized specimen configurations (left: front view; right: back view). (a) Panelized specimens without blocking and (b) panelized specimens with blocking.

transportation limitation, the width of these prefabricated floor panels is usually limited to 3.6 m (12 ft). As a result, typical panelized floor construction will incorporate several panel-to-panel joints. Furthermore, for handling purposes a continuous joist or rim board members would normally be installed around the perimeter of the floor panel. With this approach there will be a double joist at every interior panel-to-panel joint location, resulting in the structural redundancy. In this section, however, the floor panel configuration was designed to eliminate the need for double joists at the interior panel-to-panel joints, while allowing for safe and efficient handling of the panels on site.

A primary function of a light-frame floor is to serve as a diaphragm that collects the lateral load and transfers it to the shear walls and foundations below the diaphragm. In a diaphragm, the sheathing panel layout, as relative to the loading direction, could affect the lateral load resistance (Yeh et al. 2016). In timber design standards of North America (American National Standards Institute/American Wood Council 2015, Canadian Standard Association 2019), six different sheathing panel arrangements relative to the applied loading for diaphragms are classified as Cases 1 to 6 as shown in Figure 1. For Cases 1 and 3, continuous panel joints are both perpendicular to framing joists but the load direction related to joists is different. In contrast, continuous

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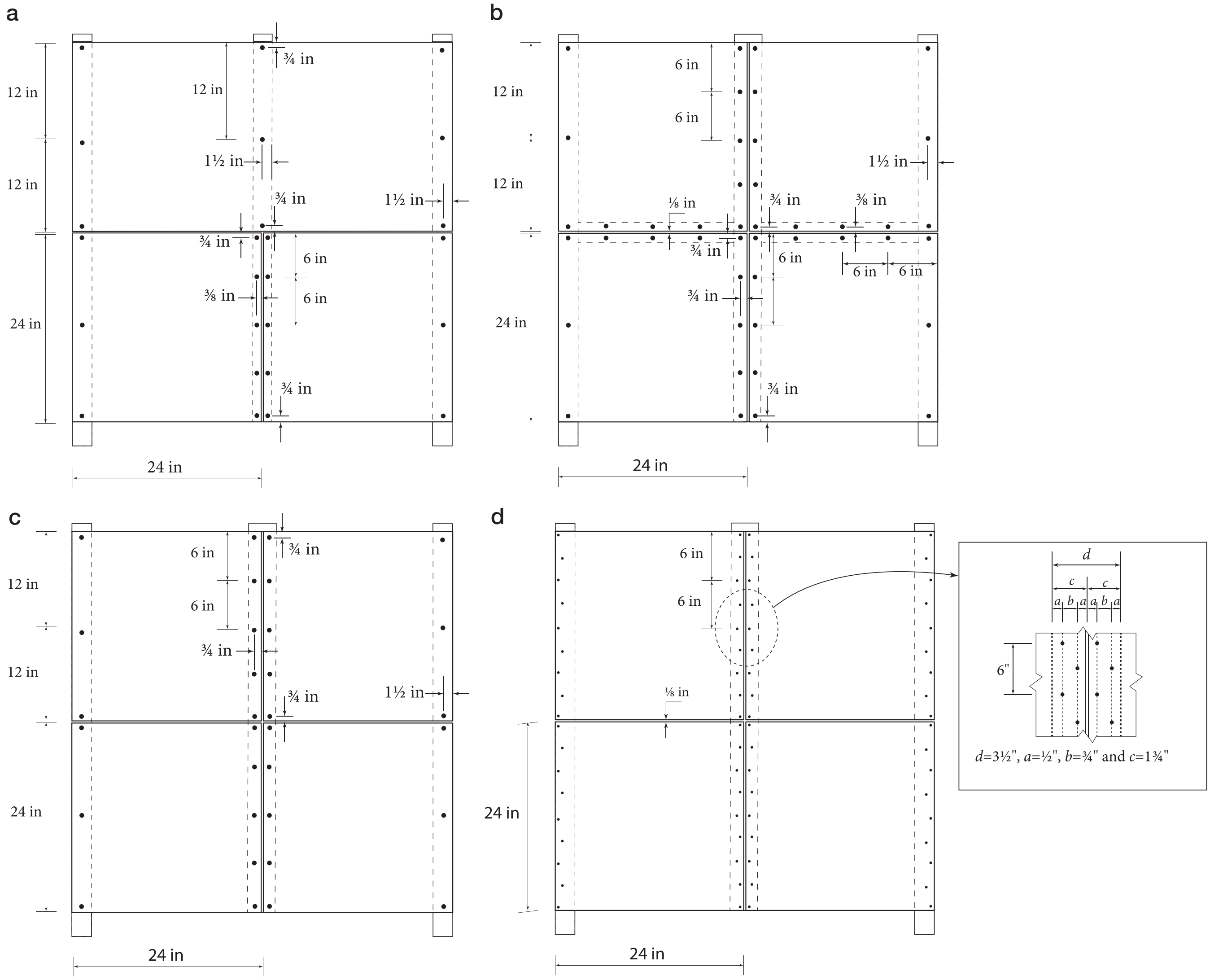

Figure 9.—Nailing patterns and dimensions (1 in = 25.4 mm, the dot represents a nail). (a) Conventional specimens without blocking; (b) conventional specimens with blocking; (c) panelized specimens without blocking; and (d) panelized specimens with blocking.

panel joints are parallel to framing joists for Cases 2 and 4 as well as Cases 5 and 6. Among these diaphragm cases, Case 1 normally has the highest lateral load resistance and Case 2 is often used in panelized systems. Therefore, in the present study, only prefabricated floor panels for diaphragms of Case 1 (Fig. 1a) were investigated for their lateral load performance.

As a result, a floor panel configuration was designated for Case 1 as shown in Figure 2 and Figure 3. The panelized floor system in Figure 2b can be constructed by two prefabricated panels as shown in Figure 3. To avoid the structural redundancy and reduce cost, only one joist is used at the panel-to-panel joint. Thus, the left-side floor panel as shown in Figure 3a should be open on the joint (i.e., no outside joist on this side) and can be connected through the side joist of the right-side panel (Fig. 3b) in the on-site construction. In order to easily install panels, the I-joist at the panel-to-panel joint should have a wide flange, say 89 mm (3.5 in). Moreover, to keep the cantilever part of oriented strand board (OSB) panels at the open side of the left panel in a stable condition during transportation or lifting, it is recommended that I-blockings be installed at the OSB edge joints as shown in Figure 4 (e.g., 1.22-m [4-ft] spacing). The flange of I-blockings is toe-nailed to I-joist framing with two nails applied on opposite sides on the top and bottom flanges, separately, as illustrated in Figure 5. More importantly, the floor sheathing panels should be nailed to I-blockings.

It is well known that the lateral load performance of diaphragms depends on four factors: sheathing thickness and layout, nailing type and spacing, provision for blocking, and width of framing members (Stalnaker and Harris 1997). In this panel configuration (Fig. 2b), the continuity of staggered sheathing panels and perimeter-chord development is disrupted, which may lead to a reduction in lateral load resistance of diaphragm. On the other hand, the wider I-joist flange, extra nails, and I-blockings at the panel-to-panel joints could increase the resistance. Therefore, it is necessary to conduct tests on wood I-joist floors built with

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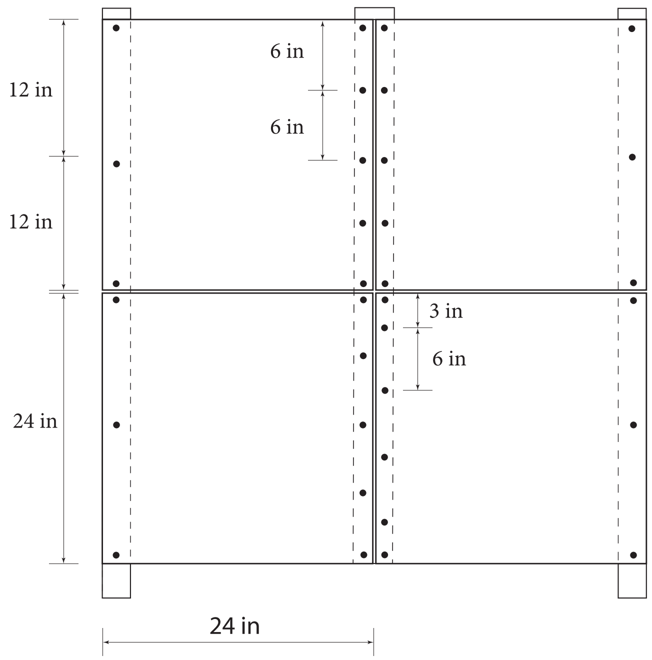

Figure 10.—Panelized specimens without blockings, with staggered nailing (1 in = 25.4 mm).

panelized panels for efficacy in achieving diaphragm action by comparing it with that of conventional stick-built floors.

Experimental Investigation on Lateral Load Performance

An experimental program was undertaken to investigate lateral load performance of wood I-joist diaphragms built with prefabricated floor panels. The conventional stick-built floors were used as reference specimens. Four primary parameters were investigated, namely sheathing layout, nailing pattern, provision of blocking, and flange width. Since the only difference between the conventional floors and panelized floors developed in this project was construction details at the location of the panel-to-panel joints in the panelized floor, testing and evaluation focused on that specific location to compare the lateral load performance between different details. Based on this rationale, a small-scale diaphragm test setup was used in lieu of a full-scale diaphragm test.

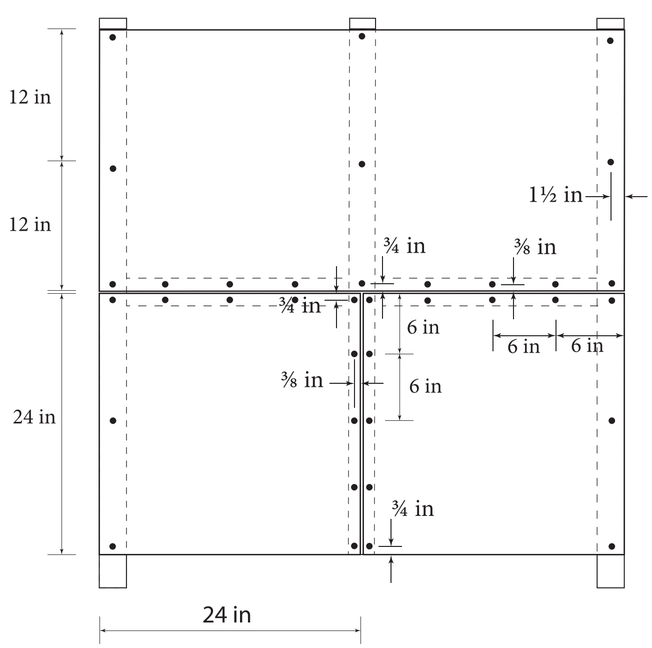

Figure 11.—Panelized specimens with blockings, with two-row nailing (1 in = 25.4 mm).

Table 1.—Wood I-joists used in specimens.

	Side framing		Middle framing		I-blockings	
Label[a]	Length, mm (in)	Joists	Length, mm (in)	Joists	Length mm (in)	Joists
CNB	1,320 (52)	IJ25	1,245 (49)	IJ25	—[b]	—
CWB	1,320 (52)	IJ25	1,245 (49)	IJ25	514 (20¼)	IJ25
PNB	1,320 (52)	IJ25	1,245 (49)	IJ35	—	—
PWB	1,320 (52)	IJ25	1,245 (49)	IJ35	501 (19¾)	IJ25
PNBS	1,320 (52)	IJ25	1,245 (49)	IJ35	—	—
PNB2	1,320 (52)	IJ25	1,245 (49)	IJ35	—	—
PNBN	1,320 (52)	IJ25	1,245 (49)	IJ25	—	—

[a] CNB = conventional specimen without blockings; CWB = conventional specimen with blockings; PNB = panelized specimen without blockings; PWB = panelized specimen with blockings; PNBS = panelized specimen without blockings with staggered nailing; PNB2 = panelized specimen without blockings with two-row nailing; PNBN = panelized specimen without blockings with a narrow-flange (63-mm) middle I-joist.

[b] Dash indicates not applicable; no blocking was used.

Test specimens

As stated above, the tests were conducted using a small-scale diaphragm test setup that allowed us to focus on the key location of diaphragm with respect to lateral load resistance for comparison purpose. Such locations are illustrated in Figure 6 for conventional and panelized floors. Taking these parts out as representations of original floors, four specimen configurations can be developed for the small-scale diaphragm test as shown in Figure 7 and Figure 8: two for conventional specimens and two for panelized ones. The difference between conventional configurations is provision of I-blockings, and they were denoted as conventional specimens without blockings (CNB) and conventional specimens with blockings (CWB) as shown in Figure 7. The same difference was found in panelized configurations, which were designated as panelized specimens without blockings (PNB) and panelized specimens with blockings (PWB) as shown in Figure 8. It should be noted that the middle joist for panelized configurations in Figure 8a and Figure 8b has a flange width of 89 mm (3.5 in), compared with conventional ones with a 63-mm (2.5-in) flange width. Figure 9 illustrates the nailing pattern for each configuration and its dimensions. It should be noted that the distance from the left end of the side joist to the center of the middle joist was 609 mm (24 in). Such an arrangement was set for the simplicity of specimen manufacturing. In construction practice, the 609 mm is measured from the center to center of joists.

In addition, two extra nailing patterns were also considered for PNB specimens, namely staggered nailing (PNBS) and two-row nailing (PNB2) as shown in Figure 10 and Figure 11, respectively. In order to study the influence of the flange width, PNB specimens with a narrow-flange

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Figure 12.—Actual test set-up (conventional specimen without blocking, no. 2).

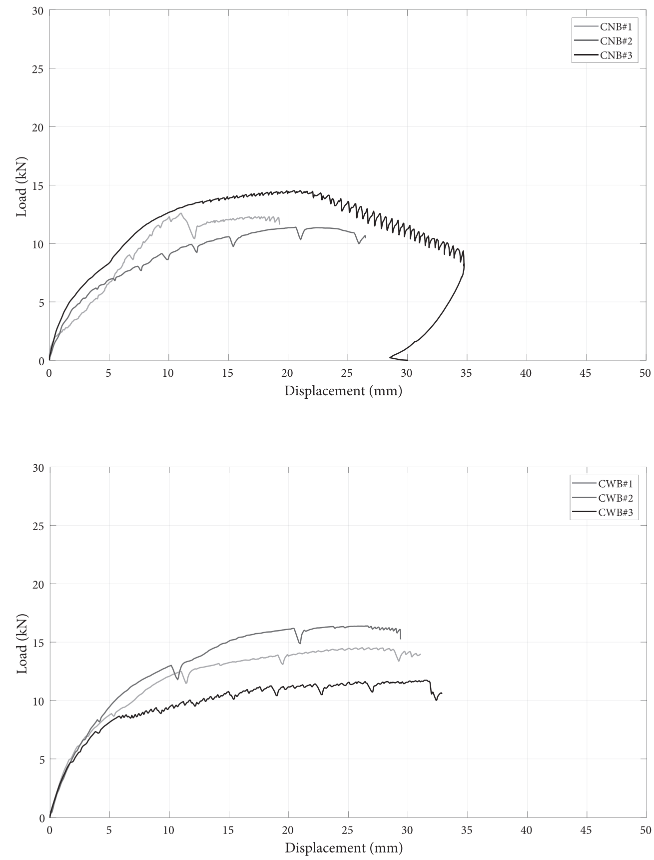

Figure 13.—Load-displacement curves of conventional specimens. CNB = conventional specimen without blockings; CWB = conventional specimen with blockings.

(63-mm) middle I-joist (PNBN) were included. The PNBN specimens have the same nailing pattern as PNB specimens. In total, seven specimen series were tested.

Materials

Test specimens were built using wood I-joists produced by a local manufacturer. Two I-joists were used for these specimens: IJ25 and IJ35, with 63-mm and 89-mm flange widths, respectively. The joist depth was 241 mm (9.5 in) and 18.5-mm-thick (0.7-in-thick) OSB was used as the sheathing panel. The nails used for fastening the OSB to the I-joist flange were 8d common nails (3.4-mm [0.13-in] diameter and 64-mm [2.5-in] length). The joist arrangements for the test groups are tabulated in Table 1. Three replicates were tested for each specimen configuration.

Test method

All specimens were tested between 12 and 36 hours after fabrication. As illustrated in Figure 12, a monotonic compressive load was applied to the top of the specimen through a 51-mm-wide (2-in-wide) and 25-mm-thick (1-in-thick) load block that bore on the top of the middle joist. The load block was centered above the middle joist, flush with the upper flange, but not in contact with the sheathing panel. A consistent cross-head displacement rate of 50 mm/min (~2 in/min) was used in the tests. Loading was stopped after a peak load was achieved. Moreover, a cable transducer was used to capture the deformation of the center of the middle joist. It should be noted that two plywood strips were installed at both front and back sides of the specimen bottom as shown in Figure 12 to ensure that any failure was caused by shear along the vertical joint and was not due to horizontal tension at the bottom of the specimen. After testing, the moisture content of the I-joist flange material was determined by using the oven-dry method in accordance with ASTM D4442 (ASTM International 2016).

Test results

The average moisture content of joist flange was about 9 percent, with most readings within 1 percent of this value. Load-displacement curves are illustrated in Figure 13 and

Table 2.—Stiffness and peak load results. See Table 1 for label definitions.[a]

Label	Stiffness (kN/mm)				CoV	Peak load (kN)				CoV
	1	2	3	Mean	(%)	1	2	3	Mean	(%)
CNB	1.0	1.9	2.1	1.7	36	12.6	11.4	14.5	12.8	12
CWB	2.4	2.2	2.5	2.4	7	14.5	16.4	11.7	14.2	16
PNB	1.2	2.1	1.5	1.6	29	17.7	16.6	19.5	18.0	8
PWB	1.9	2.3	1.8	2.0	13	22.1	24.1	23.6	23.3	4
PNBS	1.1	1.6	1.3	1.4	19	19.8	18.8	16.8	18.4	8
PNB2	2.5	1.9	2.4	2.3	13	27.5	25.0	24.1	25.5	7
PNBN	1.7	1.4	0.8	1.3	36	17.7	18.8	16.8	17.8	6

[a] CoV = coefficient of variation. #1, #2, and #3 indicate specimen labels.

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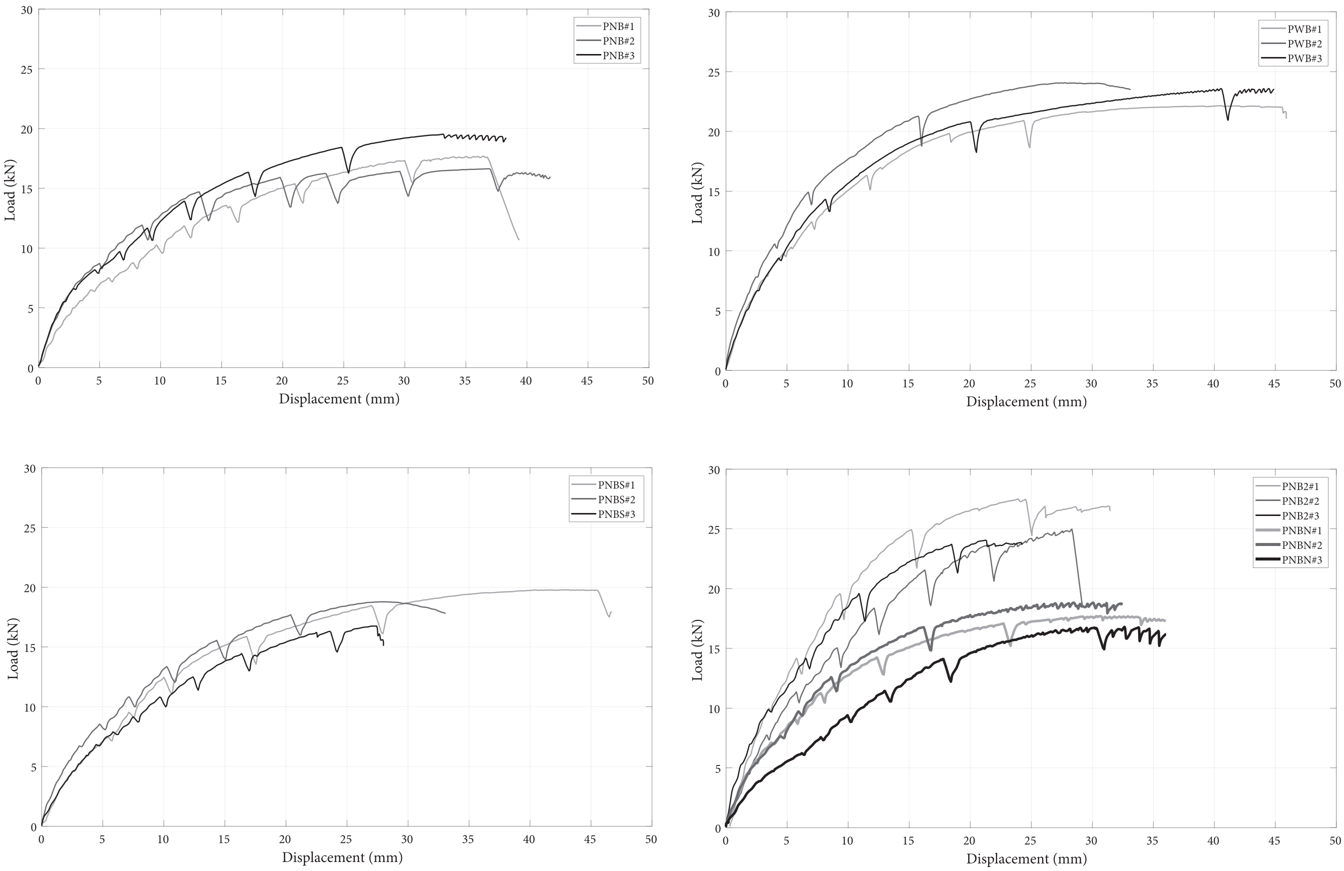

Figure 14.—Load-displacement curves of panelized specimens. PNB = panelized specimen without blockings; PWB = panelized specimen with blockings; PNBS = panelized specimen without blockings with staggered nailing; PNBN = panelized specimen without blockings with a narrow-flange (63-mm) middle I-joist.

Figure 14 for conventional and panelized specimens, respectively. The values of stiffness and peak load obtained for each specimen and the mean values and coefficient of variation are presented in Table 2. Furthermore, mean stiffness and peak load for each specimen configuration are compared as shown in Figure 15. Stiffness of a test specimen was determined by calculating the slope of the load-displacement response between 10 and 40 percent of the peak load. As shown in Table 2, the variability of stiffness is similar between conventional specimens and related panelized specimens. Figure 15 indicates that the stiffness values of conventional specimens (CNB and CWB) are higher than those of panelized specimens (PNB, PWB, PNBS, and PNBN). Furthermore, it can also be seen in Figure 15 that the I-blockings and two-row nailing pattern significantly increase specimen stiffness. The influence of staggered nailing and flange width on stiffness was minor.

For the strength (i.e., peak load), the variability of conventional specimens is notably higher than those of panelized ones. As illustrated in Figure 15, the strength of

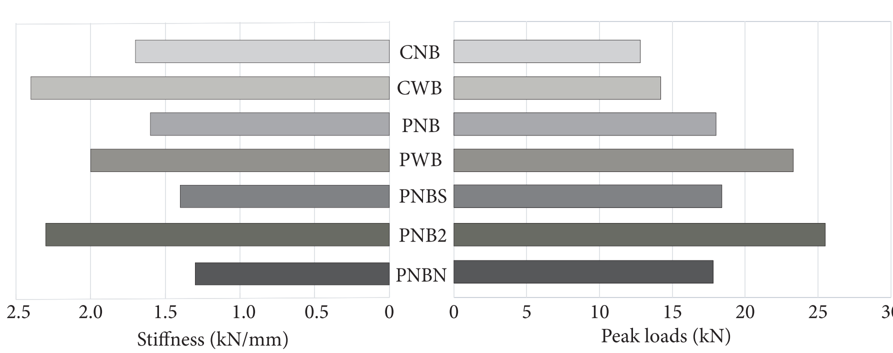

Figure 15.—Comparisons of mean values of stiffness and peak load. CNB = conventional specimen without blockings; CWB = conventional specimen with blockings; PNB = panelized specimen without blockings; PWB = panelized specimen with blockings; PNBS = panelized specimen without blockings with staggered nailing; PNB2 = panelized specimen without blockings with two-row nailing; PNBN = panelized specimen without blockings with a narrow-flange (63-mm) middle I-joist.

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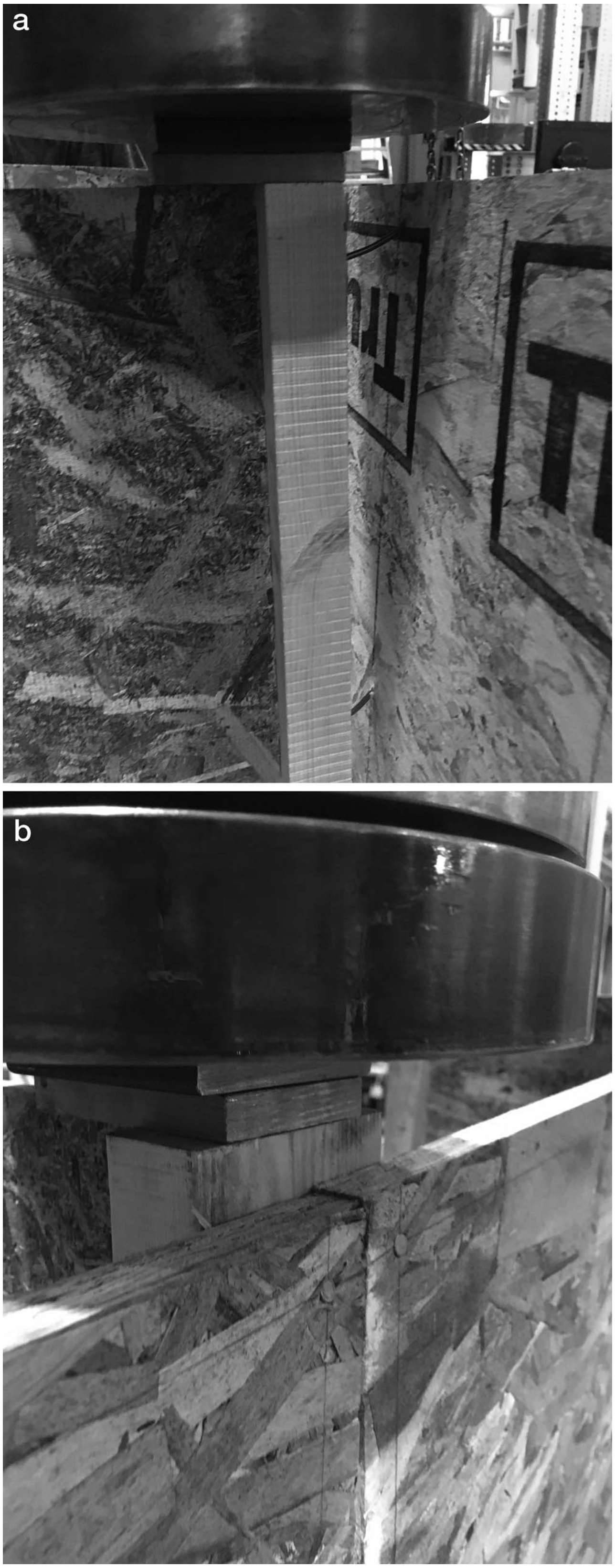

Figure 16.—The upper panel conditions after peak loads for two typical specimens: (a) conventional specimen with blocking, no. 3 and (b) panelized specimen without blockings with staggered nailing, no. 1.

Figure 17.—Typical failure mode for panelized specimens (panelized specimen without blockings with staggered nailing, no. 1).

panelized specimens (PNB, PWB, PNBS, and PNBN) was far greater than that of associated conventional specimens (CNB and CWB). Part of the reason may be because the failure modes are different for these two categories. For conventional specimens, the peak loads occurred when the nails in the upper OSB panel were pulled out from the joist flange, which can be observed in Figure 16a. However, for all panelized specimens, nail pull-out failure at the upper OSB panels did not happen. Rather, as shown in Figure 16b, after reaching the peak load, the two upper OSB panels rotated (Fig. 17), leading to excessive bending of the nails in the vertical joint.

Similar to stiffness, the I-blocking and two-row nailing considerably increase the strength. In particular, it was found that the presence of I-blocking would increase the strength by 10 percent for conventional specimens and by 30 percent for panelized PNB and PWB specimens. When comparing the peak loads of PNB and PNB2 specimens, it can be noted that the use of two-row nailing improved strength by about 40 percent. The differences in strengths of PNB, PNBS, and PNBN specimens were negligible. Thus, it can be argued that the staggered nailing and wider flange of the middle joist do not have significant influence on the strength.

Conclusions

The present research investigated the lateral load performance of panelized wood I-joist floor systems by comparing them with conventional stick-built floors. In summary, the test results indicate that a small decrease in lateral stiffness occurs for panelized floor specimens in comparison with that of conventional specimens. However,

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the lateral strength of panelized specimens is significantly higher than that of conventional ones. The presence of I-blockings and two-row nailing pattern significantly increased the stiffness and strength of both conventional and panelized specimens. Thus, the reduced stiffness of panelized floors can be recovered by installing blockings and extra nails. In addition, staggered nailing and the flange width had a negligible effect on lateral load performance. Finally, the use of a small-scale diaphragm test setup in the present study was successful in identifying suitable panel-to-panel connection details that could be further evaluated in additional full-scale diaphragm tests before implementation by the prefabricated housing industry. The test program was also beneficial for structural engineers to understand the structural performance of panelized floor systems with customized panel-to-panel joints tested in this research.

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