Performance of Full-Scale I-Joist Diaphragms

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1 Introduction

Light-frame wood diaphragms constructed with prefabricated wood I-joists have been used in construction of thousands of buildings in North America for more than 30 years. It has always been assumed by the I-joist manufacturers and design engineers that the structural performance of diaphragms constructed with I-joists made of flanges with thickness of 33 mm (1-5/16 inches) or greater will meet the diaphragm design values published in the engineering standard, such as the *Special Design Provisions for Wind and Seismic* (SDPWS) [AWC, 2015], or the U.S. building code [ICC, 2015]. This minimum flange thickness is based on the minimum nail penetration required for the development of full lateral resistance of single nails.

The historical performance in the field supports such an assumption as there have been no reported diaphragm performance issues for those buildings so constructed. However, there are limited full-scale I-joist diaphragm test data that are publically available [Waltz and Dolan, 2010] even though some I-joist manufacturers may have proprietary test data for I-joists made of thin structural composite lumber (SCL) flanges (as thin as 28 mm or 1-1/8 inches in thickness) to demonstrate its structural equivalency to light-frame diaphragms constructed with solid-sawn lumber joists.

In recent years, however, a concern has been raised on the I-joist diaphragm performance based on the experience learned from thin-flange I-joist diaphragm tests. It was reported that I-joist flanges are prone to splitting when subjected to full-scale diaphragm loading, resulting in a reduction in the diaphragm lateral load capacity. In conjunction with a variety of flange sizes, grades, and/or species, the concern over structural performance of I-joist diaphragms has prompted the International Code Council Evaluation Service (ICC-ES), a code evaluation agency in the U.S., to take the position that unless full-scale diaphragm test data are provided, the proprietary code evaluation report (similar to the European Technical Approval, ETA) will not specifically recognize I-joist diaphragm applications regardless of the flange materials and sizes.

To address this deficiency in full-scale I-joist diaphragm test data, APA – The Engineered Wood Association, which represents more than 70% of I-joist production in North America today, initiated a study on I-joist diaphragm performance using both small-scale and full-scale I-joist diaphragm tests. This paper provides the small-scale and full-scale diaphragm test results.

2 Objectives

This study was designed to evaluate the lateral load performance of light-frame diaphragms constructed with prefabricated wood I-joists as the primary framing members. The test results were intended for comparison with diaphragm design values published in the SDPWS or the U.S. code, which were developed based on full-scale diaphragm tests using solid-sawn lumber joists. Due to the small number of full-scale diaphragm tests conducted in this study, it is not the intent of this study to establish new diaphragm design values for I-joist diaphragms. This study was limited to I-joists made of solid-sawn lumber flanges due to the commonality in lumber-flange sizes and grades. However, it is not the intent of this study to preclude the use of the results obtained from this study for I-joists made of structural composite lumber flanges when appropriate.

3 Materials and Methods

3.1 General Consideration

Full-scale diaphragm tests are expensive and time-consuming. With a variety of material variables that could influence the diaphragm lateral load capacities, such as flange species, grade, and dimension, web materials and thickness, floor sheathing thickness, and fastener type and size, it is impractical to conduct full-scale diaphragm tests to quantify the relative influence of each variable to the diaphragm lateral load capacities. As a result, a small-scale test method that can serve as a screening tool to compare the relative diaphragm performance is highly desirable so that the full-scale diaphragm tests can focus only on the diaphragm assemblies with critical variables to save the laboratory time and material cost.

3.2 Small-Scale Diaphragm Tests

The critical connection for a light-frame diaphragm subjected to lateral loads is usually the corner joint where 4 sheathing panels are connected to the same floor (or roof) framing member, as shown in Figure 1. At this location, nails are closely spaced in high density, which is prone to flange splitting. With this in mind, a small-scale test method that can capture the rotation of sheathing panels at the corner joint and the potential for flange splitting was developed by the I-joist industry and has been adopted into ICC-ES *Acceptance Criteria for Prefabricated Wood I-joists*, AC14 [ICC-ES, 2014]. This small-scale test method, through the I-joist industry experience, has demonstrated its capability in screening the material variables that influence the diaphragm lateral load capacities.

Figure 1. Deformation shape of a light-frame diaphragm showing the corner joint as circled

Figure 2 shows the schematic drawings of the small-scale diaphragm assembly. It is understood that the entire diaphragm behaviour can be affected by more than the corner joints. Therefore, this small-scale test results can only be used to provide a relative comparison of the lateral load performance for a range of material variables. An attempt to correlate the small-scale test results to the published diaphragm design values has proven to be challenging.

3.2.1 Test Matrix

In general, there are 3 major wood species or species groups, Douglas-fir (DF), black spruce (BS), and spruce-pine-fir (SPF), which have been used as I-joist lumber flanges in North America. For each wood species or species group, there are different lumber grades. However, the vast majority of production in North America for I-joists made of lumber flanges uses 1650f-1.5E and 2100f-1.8E MSR lumber, or equivalent. Therefore, the matrix developed for this study for small-scale diaphragm tests was based on these 2 lumber grades. For other lumber grades and species, which is relatively rare in commercial production volume, can be evaluated using the data obtained from this study as benchmarks.

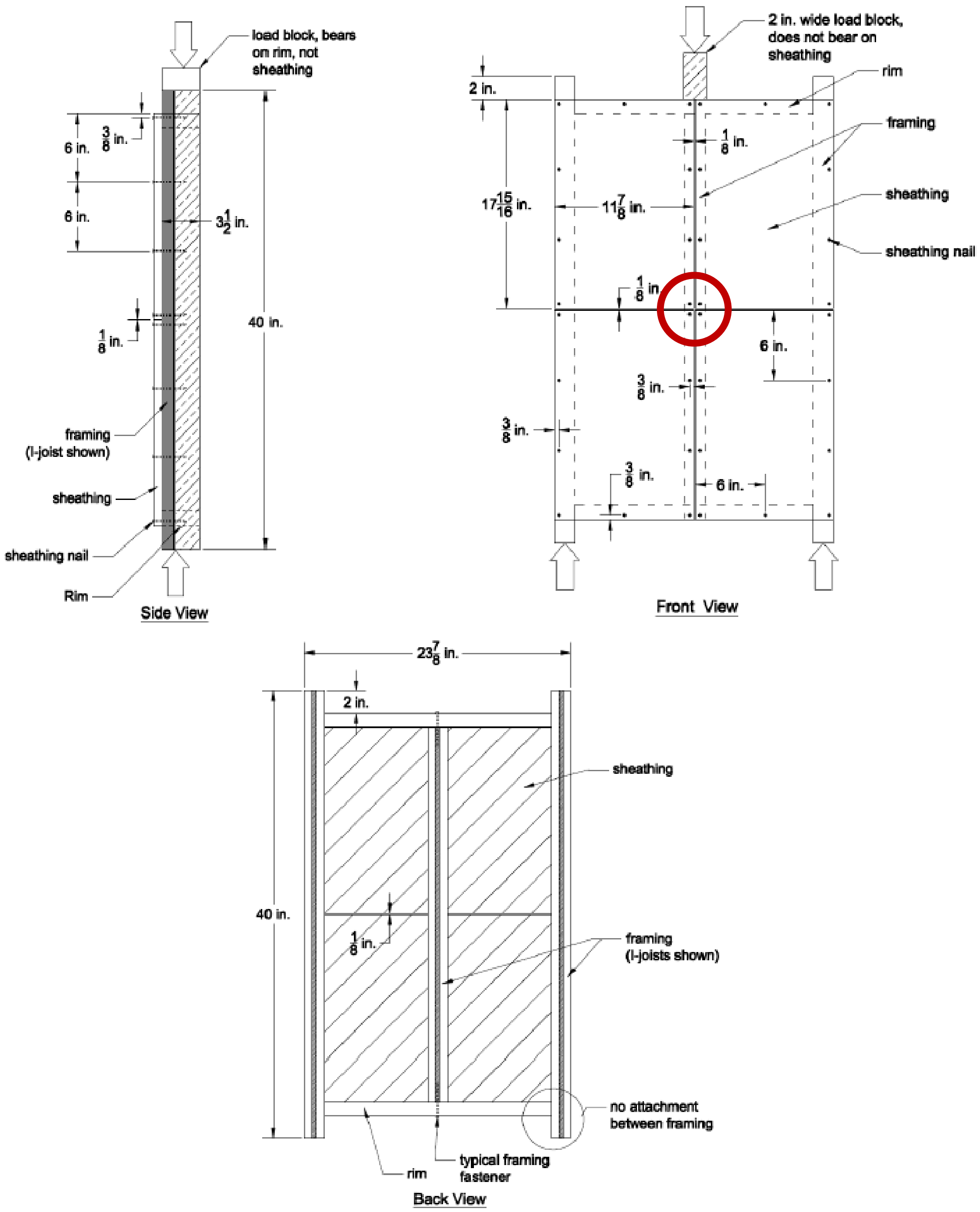


Figure 2. Schematic drawings for small-scale diaphragm test assembly (1 inch = 25.4 mm)

The smallest lumber flange dimension is 38 mm x 64 mm (1-1/2 inches x 2-1/2 inches) in the North American I-joist production today. As such, small-scale diaphragm tests were conducted with this flange size on 1650f-1.5E and 2100f-1.8E flanges (2 flange grades in total) for DF, BS, and SPF (3 species in total). This resulted in 6 small-scale diaphragm test series in total. As previously mentioned, these small-scale diaphragm assemblies were tested to determine the most critical I-joist series for subsequent full-scale diaphragm tests. Figure 3 shows the actual small-scale diaphragm assemblies.

Figure 3. Actual assemblies for small-scale diaphragm tests

3.2.2 Specimen Construction

Ten replicates of each small-scale diaphragm series were tested following ICC-ES AC14 requirements. The sheathing, rim board, and nails were matched for all assemblies tested in this study. A 25-mm (1-inch) thick oriented strand board (OSB) rim board was used as the diaphragm sheathing to reduce the probability of sheathing failure during testing because the intent was to make relative comparison of the diaphragm assembly performance as influenced by the flange splitting.

Laminated strand lumber (LSL) was used as the horizontal rim on the top and bottom of each assembly. The I-joist flange under evaluation included a 51-mm (2-inch) web section and served as the framing member of the assembly. Nails with a shank diameter of 3.8 mm (0.148 inch) and length of 76 mm (3 inches), known as 10d common nails in the U.S., were used to attach the sheathing to the framing (i.e., I-joist flange).

3.2.3 Test Method

All assemblies were tested in the as-received conditions at the APA Research Centre in Tacoma, Washington. As prescribed in ICC-ES AC14, all assemblies were tested within the same time period (± 1 hour) between fabrication and loading. A compressive load was applied to the top of the assembly through a 51-mm (2-inch) wide load block that bore on the rim at the top of the assembly (see Figures 2 and 3). The load block was flush with the rim and centred, and did not bear on the sheathing. At the base, the assembly was supported by a flat test bed on the exterior framing members. The peak load and failure mode of each assembly were recorded.

3.2.4 Test Results for the Small-Scale Diaphragm Assemblies

Test results for the small-scale diaphragm assemblies are summarized in Table 1. All assemblies failed due to framing splitting at the mid-height sheathing-to-framing connection (corner joint). The moisture contents of the flanges from the 6 test series were within 3% of each other, thereby complying with the requirements of ICC-ES AC14 for the purpose of relative performance comparison.

Table 1. Summary statistics for small-scale diaphragm test results [(a)]

	2100f-1.8E MSR			1650f-1.5E MSR		
	DF	BS	SPF	DF	BS	SPF
Observations	10	10	10	10	10	10
Mean, kN (lbf)	23.6 (5300)	26.7 (5995)	26.1 (5863)	25.7 (5767)	23.6 (5299)	25.4 (5711)
COV	0.154	0.064	0.066	0.072	0.093	0.071
Minimum, kN (lbf)	16.3 (3673)	24.3 (5471)	23.7 (5328)	23.2 (5208)	20.6 (4634)	22.1 (4978)
Maximum, kN (lbf)	29.6 (6661)	30.0 (6754)	29.5 (6664)	29.3 (6578)	26.0 (5854)	28.7 (6449)

(a) All specimens failed as a result of flange splitting.

As shown in Table 1, the lowest mean peak load was from I-joists made of 1650f-1.5E black spruce flanges and 2100f-1.8E Douglas-fir flanges, as highlighted. While the mean peak load values between these 2 flange series were virtually the same (23.6 kN or 5300 lbf), the coefficient of variation (COV) of the data differed: 9.3% for 1650f-1.5E black spruce and 15.4% for 2100f-1.8E Douglas-fir flanges. As a result, I-joists made of 2100f-1.8E Douglas-fir flanges were selected for the full-scale diaphragm tests due to its higher variability. This was not unexpected as Douglas-fir is known to be more prone to nail splitting than black spruce and spruce-pine-fir. Besides, the higher grade lumber, which is denser, is expected to have a higher nail splitting tendency than the lower grade lumber.

3.3 Full-Scale Diaphragm Tests

The current light-frame diaphragm lateral load capacities published in the SDPWS or the U.S. code were developed based on full-scale diaphragm tests conducted by APA in 1950's through 1970's [Tissell and Elliott, 2000]. There were a variety of diaphragm sizes that were evaluated, ranging from 3.7 m x 12.2 m (12 feet x 40 feet), 7.3 m x 7.3 m (24 feet x 24 feet), to 4.9 m x 14.6 m (16 feet x 48 feet). The higher aspect ratio diaphragms behave like long bending members, while the lower aspect ratio diaphragms act like short shear beams. For the purpose of this study – comparing the diaphragm lateral load capacities with the published values for diaphragms constructed with solid-sawn lumber joists, the full-scale diaphragm tests were conducted using a diaphragm dimension of 7.3 m x 7.3 m (24 feet x 24 feet) in accordance with ICC-ES AC14 to produce the maximum shearing effect.

The sheathing layout, as relative to the loading direction, could affect the diaphragm lateral load capacities. In the SDPWS or U.S. code, the diaphragm design values depend on diaphragm “load cases,” as shown in Figure 4. The Canadian code follows the same classification, except that Cases 5 and 6 are not recognized. Overall, diaphragms constructed in accordance with Cases 5 and 6 are considered more critical than other diaphragm configurations due to the existence of continuous panel joints in both loading directions. On the other hand, diaphragms constructed in accordance with Case 1 or Case 2 are considered relatively strong due to its “interlocking” effect with discontinuous panel joints.

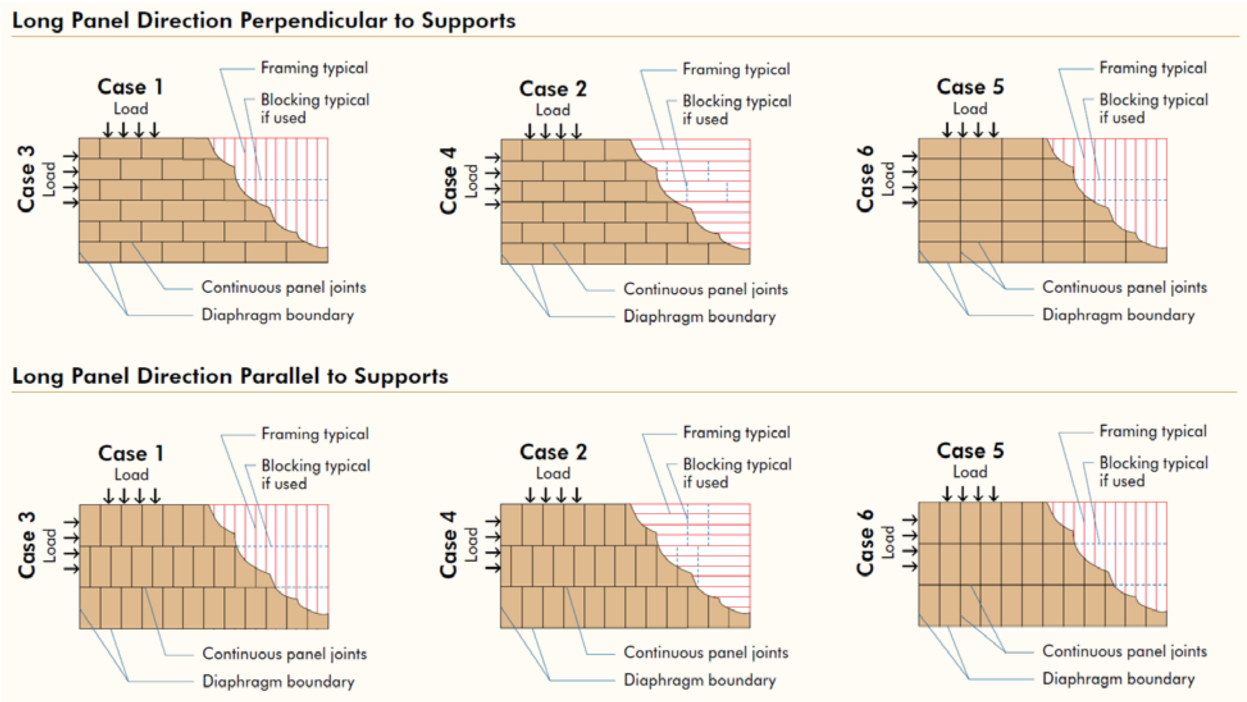


Figure 4. Diaphragm cases in the U.S. building code

In addition to the diaphragm cases, the diaphragm lateral load capacities also depend on sheathing grade and thickness, nail size and spacing, and the presence of panel blocking (i.e., blocked diaphragms) or not (i.e., unblocked diaphragms). For the purpose of this study, a full-scale diaphragm test matrix was developed to cover a range of diaphragm design values, as shown in Table 2.

It is important to note that this test matrix took into account the fact that the closest nail spacing recommended for I-joist flanges is typically limited to 102 mm (4 inches) on centre. In addition, it recognized that the diaphragm lateral load capacities are different between blocked and unblocked diaphragms. As a result, a total of 4 test series were included in the full-scale diaphragm test matrix.

Table 2. Diaphragm Assemblies

<table>
<tr><th rowspan="2">Diaphragm ID</th><th rowspan="2">Nail</th><th colspan="3">Nail Spacing, mm (in.)</th><th rowspan="2">Case</th><th rowspan="2">Panel Thickness, mm (in.)</th><th rowspan="2">Blocked?</th></tr>
<tr><th>Field</th><th>Diaphragm Boundary</th><th>Panel Edges</th></tr>
<tr><td>1A, 1B, 1C</td><td rowspan="4">10d [(a)]</td><td rowspan="4">305 (12)</td><td>102 (4)</td><td>102 (4)</td><td>5</td><td rowspan="4">15 (19/32)</td><td>Yes</td></tr>
<tr><td>2A, 2B</td><td rowspan="3">152 (6)</td><td rowspan="3">152 (6)</td><td>1</td><td rowspan="2">No</td></tr>
<tr><td>3A, 3B</td><td rowspan="2">5</td></tr>
<tr><td>4A</td><td>Yes</td></tr>
</table>

[(a)] 10d nails has 3.8 mm (0.148 inch) in diameter and 76 mm (3 inches) in length.

For Series 1 (Case 5 blocked), which was considered as the most difficult diaphragm configuration for the purpose achieving the targeted design value, 3 replicates were tested to provide a higher data confidence. For Series 2 (Case 1 unblocked) and 3 (Case 5 unblocked), 2 replicates were tested in accordance with ICC-ES AC14. On the other hand, as the test results from Series 1 through 3 were quite convincing, only 1 replicate was tested for Series 4 (Case 5 blocked with a wider nail spacing than Series 1).

3.3.1 Full-Scale Diaphragm Test Setup

The full-scale diaphragm test setup followed the simple-beam method of ASTM E455, *Standard Method for Static Load Testing of Framed Floor or Roof Diaphragm Constructions for Buildings* [ASTM, 2016], as shown in Figure 5, using I-joists conforming to ASTM D5055 [ASTM, 2016] and plywood sheathing conforming to DOC PS1 [DOC, 2009].

During testing, loads from a 1335-kN (300-kip) actuator were distributed into a wide-flange steel beam. From each end of this steel beam, a wide-flange steel beam was used to distribute the load into the diaphragm through 2 load points. V-blocks were used at the connection points to permit the rotation of steel loading beams. At the diaphragm reactions (see Figure 5), bearing plates were installed with a hinge on one end and rollers on the other. A load cell was installed at each reaction point to measure the actual test load up to the diaphragm failure. The diaphragm was retrained from out-of-plane movement by steel plates overlaid with Teflon at parallel edges of the diaphragm.

All diaphragm assemblies were constructed with 241-mm (9-1/2-inch) deep I-joists made of 38 mm x 64 mm (1-1/2 inches x 2-1/2 inches) flanges and 9.5-mm (3/8-inch) OSB web. The I-joists were spaced at 610 mm (24 inches) on centre and sheathed with 15 mm (19/32 inch) plywood floor sheathing. Each diaphragm assembly was suspended on 8 small support blocks sized to maintain the diaphragm in a level horizontal plane. Rollers were placed between the diaphragm assembly and the support blocks to avoid friction. The I-joist right under each load point was reinforced with

1220-mm (4-ft) long filler blocks placed on both sides of I-joists between flanges to prevent localized crushing failures of the diaphragm. The perpendicular joist under the load points was also reinforced with filler blocks. In addition, the corners of the loaded edge and the reaction points of the diaphragm were also reinforced.

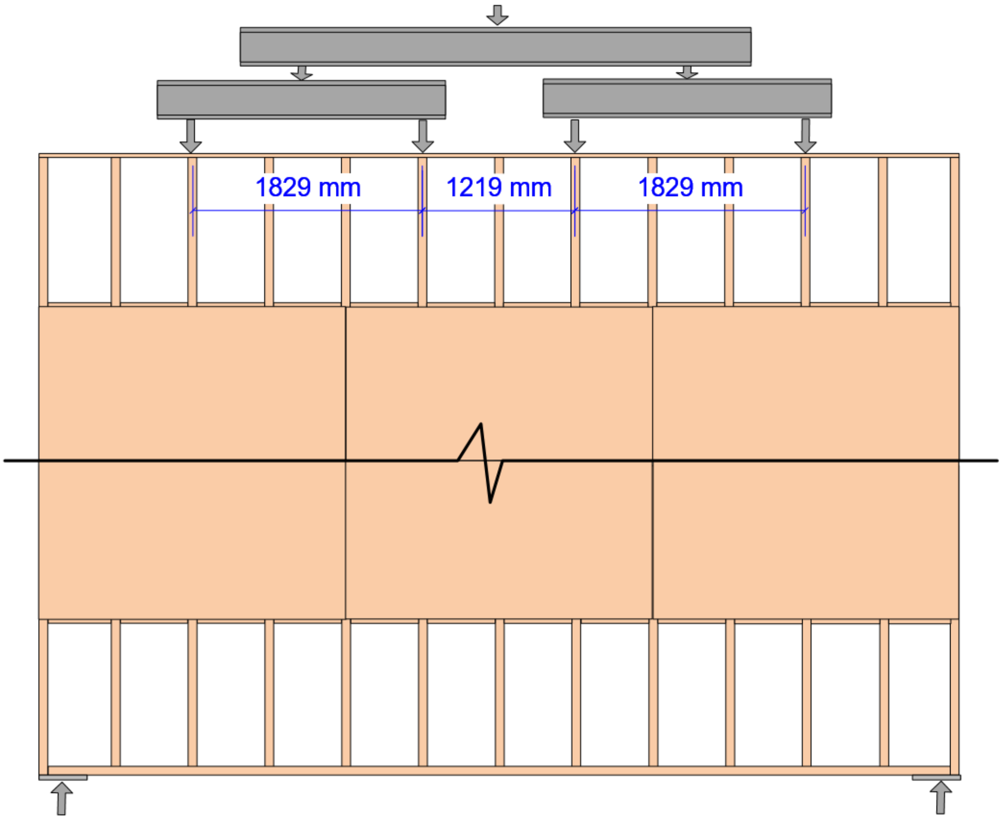


Figure 5. Full-scale diaphragm test setup (1 mm = 0.0394 in.)

For blocked diaphragms, the blocking was provided by 38 mm x 89 mm (1-1/2 inches x 3-1/2 inches) Douglas-fir lumber cut to length to ensure correct joist spacing. The blocking was installed flatwise and held in place using 2 toe-nails of 2.9 mm (0.113 inch) in diameter and 51 mm (2 inches) in length at each end of the lumber blocking.

3.3.2 Test Method

All diaphragm tests were performed in accordance with ASTM E455 at the APA Research Centre in Tacoma, Washington. Two deviations to the standard were noted: (1) the loading on the diaphragms was changed from 2 load points to 4 load points to be consistent with the historical tests used to derive the diaphragm design values in the SDPWS or the U.S. code and (2) deflection measurements were taken at each reaction and mid-span. These deviations are not expected to affect the diaphragm test results.

4 Results and Discussion

4.1 Unsheathed Diaphragm Frame Stiffness

ASTM E455 requires that the bare diaphragm frame (without sheathing) be determined to establish its load-deformation characteristics before attaching the diaphragm sheathing. According to the standard, if the frame has a stiffness equal to or less than 2% of the total diaphragm assembly, no adjustment of test results is necessary. Therefore, stiffness measurements were made on 1 frame each from Series 1, 2, and 3 before the diaphragm sheathing was applied. Table 3 shows the test results.

Table 3. Diaphragm Frame Stiffness Test Results [(a)]

ID	Case	Blocked?	Design Load [(b)], N/mm (lbf/ft)	Stiffness [(b)], N/mm (lbf/in.)	Displacement [(b)], mm (in.)
1	5	Yes	7.0 (480)	32.7 (187)	3.3 (0.131)
2	1	No	4.7 (320)	18.9 (108)	4.8 (0.189)
3	5		3.5 (240)	18.0 (103)	3.3 (0.131)

[(a)] Since the unsheathed frame stiffness for Series 1 is substantially less than 2% of the sheathed diaphragm stiffness, unsheathed diaphragm frame stiffness for Series 4 was considered unnecessary.

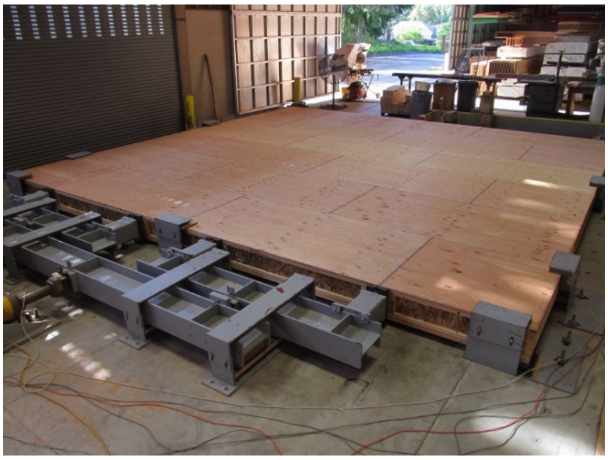
[(b)] Value at design load published in the U.S. code, which is based on the peak load divided by 2.8.

As shown in Table 3, the stiffness values of the unsheathed diaphragm frames are small and variable. The frame stiffness was calculated as the slope of a line in the load and displacement plot between the origin (after removal of slack of the system) and the diaphragm design load, which is equal to the peak load divided by 2.8. Comparisons of the unsheathed frame stiffness with that of the corresponding sheathed diaphragms (see Section 4.2 below) show that the unsheathed diaphragm stiffness was substantially lower than 2% of the sheathed diaphragm stiffness. As a result, no adjustments to the diaphragm test results were necessary based on ASTM E455.

4.2 Sheathed Diaphragm Test Results

The typical failure modes for the diaphragms are shown in Figures 6 and 7 for Case 5 blocked and unblocked diaphragms, and Case 1 unblocked diaphragms, respectively. Failure of the diaphragms followed similar mechanisms as that constructed with solid-sawn lumber joists [Tissell and Elliott, 2000]. The primary failure mode was flange splitting caused by panel sheathing rotation, i.e., tension perpendicular-to-grain failure of the top flanges. This was especially true for Series 2 and 3 (unblocked diaphragms). In some instances, it was observed that the sheathing nails yielded and finally failed by tearing out of the panel edge, pulling through the sheathing, or withdrawing from the framing. Severe nail withdrawal was thought to be a result of flange splitting, i.e., splitting occurred first allowing the nails to withdraw. In some instances, panel buckling also occurred (see Figure 6).

Figure 6. Diaphragm failure modes (Case 5 Blocked at left and Case 5 Unblocked at right)



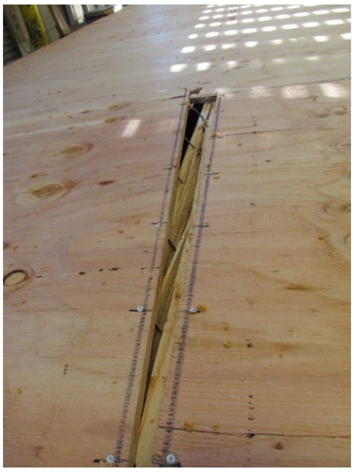


Figure 7. Diaphragm failure modes (Case 1 Unblocked)

A typical load-deformation curve from a diaphragm test is shown in Figure 8. Average peak loads, stiffness at design load, stiffness at two times design load, stiffness at peak load, displacement capacity, and ductility (displacement capacity divided by displacement at design load) are presented in Table 4.

4.3 Discussion

As noted from Table 4, the adjacent nails within a row on the diaphragm boundary for Series 1 were offset (staggered) by 12.7 mm (1/2 inch). This was applied to the tested diaphragms to avoid excessive flange splitting due to the close nail spacing of 102 mm (4 inches). This nail staggering was unnecessary for Series 4 due to an increased nail spacing to 152 mm (6 inches). In addition, as the test results for Series 4, as shown in Table 4, showed a load factor of 3.4, which is significantly greater than the code-recognized minimum load factor of 2.8, only 1 replicate of this assembly was deemed necessary.

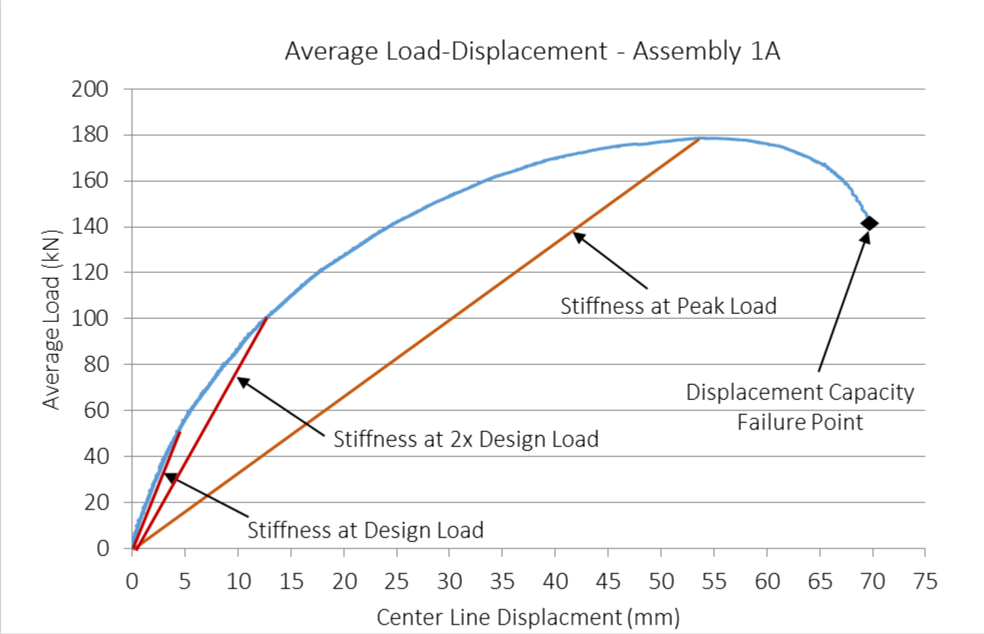


Figure 8. Typical load-displacement curve (1 kN = 224.8 lbf; 1 mm = 0.0394 in.)

It can be also seen from Table 4 that the ductility of the diaphragms is in a range of 14 and 37. Light-frame shear walls are expected to have a ductility of not less than 11, as documented in ASTM D7989 [ASTM, 2015]. Therefore, the I-joist diaphragms tested in this study can be considered to be as ductile as light-frame shear walls.

Test results from Table 4 indicate that the average load factors for Series 1 (Case 5 blocked), 2 (Case 1 unblocked), 3 (Case 5 unblocked), and 4 (Case 5 blocked with a wider nail spacing) are 3.21, 2.99, 3.17, and 3.38, respectively. These load factors exceed the code-recognized minimum load factor of 2.8 for light-frame diaphragms in the U.S. Therefore, the diaphragms constructed with I-joists made of solid-sawn lumber flanges of at least 38 mm x 64 mm (1-1/2 in. x 2-1/2 in.) can be designed with corresponding diaphragm design values published in the U.S. code provided that the nail spacing is not closer than 102 mm (4 inches) on centre. In addition, when the nail spacing is less than 152 mm (6 inches), the adjacent nails within a row on the diaphragm boundary shall be staggered by 12.7 mm (1/2 inch).

5 Conclusions

Results obtained from this study support the following conclusions:

1) Test results obtained from this study show that the diaphragms constructed with I-joists made of solid-sawn lumber flanges of 2100f-1.8E MSR or lower grades, or equivalent, with a minimum dimension of 38 mm x 64 mm (1-1/2

Table 4. Full-Scale Diaphragm Test Results

ID	Case	Blocked?	Design Load [a], N/mm (lbf/ft)	Peak Strength, N/mm (lbf/ft)	Load Factor [b]	Stiffness at Design Load, kN/mm (lbf/in.)	Stiffness at 2x Design Load, kN/mm (lbf/in.)	Stiffness at Peak Load [c], kN/mm (lbf/in.)	Displ. Capac-ity [d], mm (in.)	Ductility [e]
1A [f]	5	Yes	7.0 (480)	24.4 (1673)	3.49	12.2 (69818)	7.7 (44138)	3.3 (18836)	69.5 (2.74)	16.6
1B [f]				20.6 (1411)	2.94	15.7 (89650)	9.1 (52009)	4.3 (24514)	47.4 (1.87)	14.5
1C [f]				22.3 (1531)	3.19	20.6 (117551)	9.7 (55385)	4.3 (24323)	50.7 (2.00)	20.4
		Mean		22.4 (1538)	3.21	16.2 (92340)	8.8 (50511)	4.0 (22558)	55.9 (2.20)	17.2
2A	1	No	4.7 (320)	14.2 (972)	3.04	7.0 (40104)	3.3 (18652)	1.9 (10761)	68.9 (2.71)	14.2
2B				13.8 (944)	2.95	7.2 (41290)	2.9 (16650)	1.7 (9830)	71.2 (2.80)	15.1
		Mean		14.0 (958)	2.99	7.1 (40697)	3.1 (17651)	1.8 (10295)	70.0 (2.76)	14.6
3A	5	No	3.5 (240)	10.7 (733)	3.05	6.6 (37770)	3.5 (20175)	1.6 (9231)	90.6 (3.57)	23.4
3B				11.5 (791)	3.29	9.3 (52844)	5.0 (28728)	1.8 (10242)	103.0 (4.06)	37.2
		Mean		11.1 (762)	3.17	7.9 (45307)	4.3 (24452)	1.7 (9736)	96.8 (3.81)	30.3
4A	5	Yes	5.3 (360)	17.7 (1210)	3.38	21.5 (122553)	8.1 (46142)	3.1 (17637)	52.7 (2.07)	29.4

[a] As published in the SDPWS or U.S. Code.

[b] Load factor is determined as the ratio between the peak strength and the design load.

[c] Stiffness at peak load is determined as the slope of a line between the origin (after slack of system removed) and the peak load.

[d] Displacement capacity is determined as the diaphragm centre-line displacement where the applied load is equal to 80% of the post-peak load.

[e] Ductility is determined as the ratio between the displacement capacity and the displacement at design load.

[f] Adjacent nails within a row of nails on the diaphragm boundary were offset (staggered) by 12.7 mm (1/2 inch).

inches x 2-1/2 inches) have load factors greater than the code-recognized minimum load factor of 2.8.

2) The diaphragms tested in this study support the use of code-recognized diaphragm design values except that the nails shall not be placed closer than 102 mm (4 inches) on centre and the adjacent nails within a row on the diaphragm boundary shall be staggered by 12.7 mm (1/2 inch) when the nail spacing is less than 152 mm (6 inches).
3) The diaphragms tested in this study exhibit ductility that is comparable with light-frame shear walls.
4) For I-joist series manufactured with proprietary structural composite lumber flanges, the small-scale test results provided in this paper can be used as a benchmark for determining the applicability of these results and whether additional full-scale diaphragm tests are necessary.

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