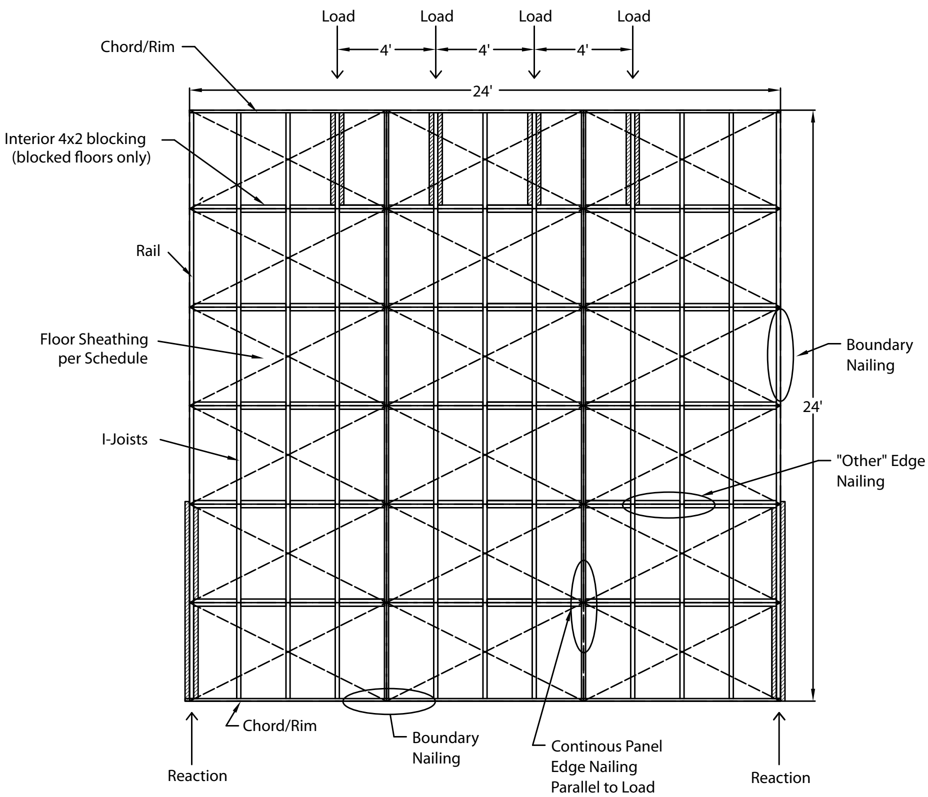

Figure 1: Typical Diaphragm Test Configuration (24 x 24 ft., Case 5 shown).

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I-Joist Diaphragm Systems

Performance Trends Observed with Full-Scale Testing

By Ned Waltz, P.E., SECB and J. Daniel Dolan, P.E.

Modern light-frame roof and floor systems routinely combine pre-fabricated wood I-joists with wood structural panel sheathing. A primary function of a light-frame floor or roof is to serve as a diaphragm that collects lateral load and transfers it to the shear walls and foundations. Diaphragm design provisions for light-frame wood construction have been successfully employed for decades and were originally developed for lumber framing. Designers often wonder if they are equally applicable to diaphragms framed with wood I-joists. The objective of this article is to provide some insight into how shear capacities are rationalized for I-joist diaphragms, and to summarize potentially useful trends observed with full-scale testing.

Diaphragm Design

Diaphragms are typically modeled as deep, in-plane beams. Perimeter framing is designed to act as tension/compression chords or struts. Wood structural panel sheathing combines with joists to serve as the "web" that transfers shear. Joists provide out-of-plane stiffening and load transfer between discrete panel sheathing elements. This makes sheathing-to-framing attachment a critical element that often defines shear capacity of the assembly.

Wood structural panel diaphragms are normally designed in accordance with provisions of the *International Building Code* (IBC) (International Code Council 2009) and the *Special Design Provisions for Wind and Seismic* (SPDWS) (American Wood Council 2008). Tables, like 2009 IBC Table 2306.2.1(1), were first developed in the 1950s and have evolved over time. The original rationalizations for these tables were based on an analysis of sheathing and attachment schedules for lumber-framed diaphragms with plywood panel sheathing. They have been subsequently modified based on results from a variety of full-scale test programs that introduced additional materials, failure modes, and design considerations.

Original I-joist framing products used laminated veneer lumber (LVL) or sawn lumber flanges with thicknesses of 1.5 inches or greater. These thicknesses were consistent with 2-inch nominal material typically used to "block" a lumber diaphragm and exceeded specified minimum fastener penetration requirements. Provided that the diaphragm configuration adhered to the manufacturer's fastener spacing recommendations to avoid splitting, and the flange material could rationalize equivalent fastener performance to an appropriate sawn lumber species, it was judged that application of shear design tables like 2009 IBC Table 2306.2.1(1) could be extended to these products.

As I-joist products are optimized, it has become common to see LVL flange thicknesses less than 1.5 inches. The industry

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Figure 2: Illustration of Test Setup (24 x 24 ft., Case 5 shown).

has long recognized that reducing flange thickness beyond a certain threshold has the potential to adversely impact sheathing nail embedment and split resistance to the point where diaphragm capacity may be influenced. International Code Council Evaluation Service (ICC-ES) acceptance criterion for I-joists defines that threshold as 1 5/16 inch (ICC-ES 2010) based primarily on sheathing nail embedment calculations. I-joist products with flanges thinner than 1 5/16 inch are subsequently required to conduct "full-scale horizontal diaphragm testing" to rationalize performance.

At present, at least two manufacturers have conducted full-scale diaphragm testing to investigate performance of I-joist product lines with flange thicknesses less than 1 5/16 inches. Both manufacturers have developed related design recommendations and limitations that are included in their evaluation reports. In general, the manufacturers have proven equivalence to a subset of the current diaphragm design tables for sawn lumber. They generally do not permit thinner flanged I-joist products to be used in the highest load applications that require the closest sheathing attachment schedules.

Full-Scale Testing

At present, Weyerhaeuser has conducted 41 full-scale tests on I-joist diaphragm systems framed with I-joists with LVL flange thicknesses between 1⅛ and 1¼ inches. *Figures 1 (page 9)* and *2* illustrate test conditions chosen to be consistent with requirements of ASTM E455 (ASTM 2004) and benchmark testing conducted with sawn lumber. A variety of I-joist materials, sheathing products, diaphragm configurations, sheathing fasteners, and fastening schedules have been tested to verify shear transfer and deformation performance capabilities. Given the high cost and relatively low variability of full-scale assembly testing, two replicates have typically been tested for each condition per the requirements of ASTM E455. Nearly all I-joist diaphragms have been tested with dimensions of 24 feet by 24 feet to focus on shear transfer capabilities and to correspond with a benchmark sawn lumber diaphragm test database.

Regardless of configuration, observed diaphragm behaviors are fundamentally consistent. Initially, diaphragms deform elastically as a deep beam without perceptible relative movement between framing and sheathing. At loads in excess of design loads, visible relative movement can be observed between adjacent sheathing panels and between panels and framing. *Figure 3* illustrates these trends for a 2009 IBC Table 2306.2.1(1) "Case 5" diaphragm configuration that aligns panel joints in both directions. Shear flow causes panels at the reactions to rotate in opposite directions towards the span centerline. The magnitude of this rotation is typically consistent between diaphragm tension and compression chords.

Due to panel geometry, the observed movement between adjacent sheathing panels is typically several times greater along long edge joints than at short end joints. The large relative movement between panel edges creates a tension perpendicular-to-grain splitting force across the framing at the fasteners for adjacent panels. At panel end joints, it induces perpendicular-to-grain forces into the framing as panel end joints rotate and the nails induce perpendicular-to-grain prying forces into the framing. Ultimately, these deformations lead to failure in some combination of panel buckling/crushing, sheathing nail withdrawal, framing splitting, and/or sheathing edge tear out. The Case 1 diaphragms tested exhibited similar behavior with the exception that panel bearing and crushing were also observed between interlocking panel rows. *Figure 4 (page 12)* illustrates the mode of failure observed for a "blocked" Case 1 diaphragm. However, as with the benchmark sawn lumber tests, the dominant failure modes observed with I-joist diaphragms were tension perpendicular-to-grain fracture of the framing and sheathing nail withdrawal. Sheathing related failure modes played a less significant role. Given that many of the potential diaphragm failure modes that limit capacity are not typically addressed by a connection analysis, the importance of test-based verification for diaphragm systems that depart significantly from the historical basis seems to be confirmed.

Performance Trends

The compiled database of full-scale I-joist diaphragm tests provides an opportunity to draw comparisons between similar test sets.

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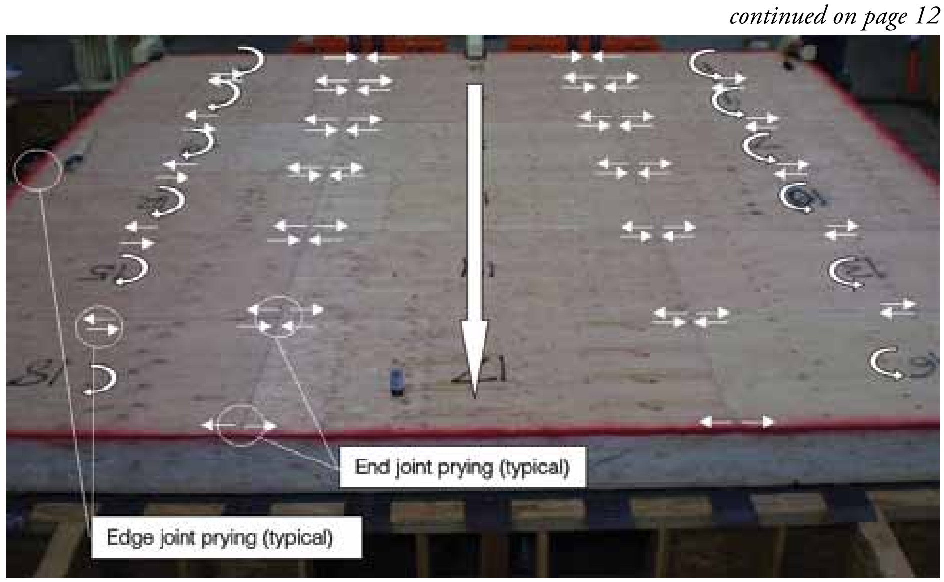

Figure 3: Typical Diaphragm Movement Mechanisms (Case 5 Shown).

While extrapolations beyond tested conditions should be approached with caution, comparisons in *Table 1* suggest trends that could be useful to the designer:

Flange Species

Douglas-fir LVL flanged I-joists outperformed their southern pine counterparts in 4 out of the 5 similar diaphragm configurations tested (Lines 1-5). This trend contradicts what is expected based on a sheathing fastener connection analysis that assumes a higher specific gravity for southern pine. This trend may be due to the difference in tension perpendicular-to-grain strengths or typical veneer thicknesses of the LVL fabricated with each species. How well these particular commercial species combinations fit the specific gravity-based fastener design models may also play a role. Regardless, it highlights that an I-joist manufacturer needs to evaluate the diaphragm performance of each primary species used for flange material. It also suggests that designers should avoid applying the diaphragm recommendations for one I-joist product to another.

LVL Veneer Thickness

The Line 6 comparison illustrates what a relatively subtle difference in I-joist product composition can have on capacity. Diaphragms framed with LVL flanges that had the same species and grade but used a slightly thicker veneer peel had about 15% less capacity. As with the last item, this would seem to confirm that diaphragm performance is product dependent. It further emphasizes that extrapolation of performance recommendations between seemingly similar manufacturers and products should be avoided.

Blocking Quality

Line 7 illustrates the influence that blocking selection can have on capacity. Even with I-joist materials taken as being a constant between tests, use of low specific gravity blocking material (0.45 vs. the intended 0.50) reduced diaphragm capacity by about 15%. This shows that selection of a blocking material is likely as important as selection of a joist and should be consistent with the design assumption. For example, avoid using spruce-pine-fir blocking if Douglas-fir diaphragm design values are targeted.

Flange Width

Comparisons on Lines 8-11 illustrate that, as with sawn lumber, wider framing results in increased capacity. This is consistent with the code design provisions and can be attributed to the fact that wider framing tends to reduce splitting and can provide for increased edge distance and staggered nail patterns that provide better load transfer.

Figure 4: Failure Modes – Framing Splitting from Panel Prying (Case 1 Shown).

Nail Size

Line 12 illustrates that a relatively intense 10d sheathing nail pattern resulted in a 16% increase in capacity relative to using 6d sheathing nails. In contrast, corresponding shear design capacities for lumber diaphragms increase by about 70%. This highlights the importance of flange splitting and the need for the manufacturer to address the resulting capacity limitations in their design guidance. Also, since the design recommendations provided by the manufacturer are typically governed by "worst case" conditions that involve larger diameter fasteners, there is likely some relative conservatism associated with smaller diameter fasteners. As with most wood connections, it is another example where more/larger fasteners do not necessarily improve performance if they lead to splitting.

Diaphragm Case

The design codes permit six different diaphragm configurations to be constructed. It is not intuitively obvious that they are all equal when it comes to I-joist diaphragm performance. The majority of tests summarized by *Table 1* were undertaken using the "Case 5" configuration illustrated by *Figures 1-3* that aligns panel joints in both directions. Since splitting was a primary concern, this was judged conservative because it maximized the number of fasteners and requires the full lateral load to be transferred through the I-joist flanges. The Line 13 comparison confirms that assumption relative to the

Table 1: Peak Strength Comparisons Between Similar Full-Scale Diaphragm Tests[1, 2]

Item	Comparison Variable[3,4] 1	Comparison Variable[3,4] 2	Load Case	Block	Sheath (in.)	I-Joist Comparison No.	Sheathing Fastener and Panel Edge Spacing: Fastener Size[5]	Perimeter Spacing	Interior Spacing	Peak Strength Ratio: *Var. 1* / *Var. 2*
1	DF LVL Flange	SP LVL Flange	5	4x2 DF	19/32	1	10d	4 in.	4 in.	**0.96**
2						2				**1.13**
3			1			3		4 in.	6 in.	**1.22**
4			5	No	23/32	1		6 in.	6 in.	**1.02**
5						2				**1.06**
6	1/7 in. LVL veneer	1/8 in. LVL Veneer	5	4x2 DF	19/32	1	10d	4 in.	4 in.	**0.86**
7	0.45 SG Blocking	0.51 SG Blocking	5	4x2 DF	19/32	1	10d	4 in.	4 in.	**0.84**
8	1.75 in. wide flange	2.3 in. wide flange	5	4x2 DF	19/32	1 vs. 2	10d	4 in.	4 in.	**0.98**
9										**0.83**
10			5	No	23/32	1 vs. 2		6 in.	6 in.	**0.85**
11										**0.86**
12	Large nails	Small nails	5	No	23/32 vs. 3/8	1	10d vs. 6d	4 in.	4 in.	**1.16**
13	Case 1	Case 5	1 vs. 5	4x2 DF	19/32	1	10d	4 in.	4 in. vs. 6 in.	**1.07**
14	24 x 24 ft.	24 x 12 ft.	5	4x2 DF	19/32	1	10d	4 in.	4 in.	**1.01**
15				No	23/32			6 in.	6 in.	**0.84**
16	6d ring	8d common	5	No	3/4 vs. 19/32	1	8d vs. 6d ring	6 in.	6 in.	**1.14**
17	0.131 in. diameter proprietary fastener	8d common	5	No	3/4 vs. 19/32	1	8d vs. proprietary	6 in.	6 in.	**1.13**

Notes:

[1]*All of the tests summarized in this table used I-joist framing with laminated veneer lumber (LVL) flanges. The "DF" and "SP" species designations represent Douglas-Fir and southern pine, respectively.*

[2]*All of the tests summarized in this table used either plywood or oriented strand board (OSB) sheathing materials.*

[3]*Except as noted in Lines 14 and 15, all of these full-scale diaphragms had dimensions of 24 ft. x 24 ft.*

[4]*The majority of the comparisons are based on the average of two tests. However, only a single diaphragm was tested in the following cases: Line 3 Variables 1 and 2, Line 14 Variable 2, and Line 17 Variable 1.*

[5]*Sheathing nail sizes were as follows: 6d - 0.113 x 2.0 in., 8d - 0.131 x 2.5 in., 10d - 0.148 x 3.0 in.*

"Case 1" configuration that requires fewer fasteners and interlocks the panels. It also suggests that there are some relative benefits for the designer to, whenever possible, favor specification of diaphragm "cases" that use interlocking panels and fewer fasteners to transfer shear.

Diaphragm Size

The 24-foot by 24-foot diaphragm size used for most of the testing summarized by *Table 1* was chosen to promote shear distortion in a condition that combined full-size sheathing elements with at least 2 interior panel joints in each direction. It also corresponded with a benchmark database for sawn lumber. As suggested by Lines 14 and 15, testing other sizes may result in slightly different answers. This highlights the importance for the manufacturer to evaluate a configuration that encourages realistic stress flows through the system if design values are being developed. The designer should also specify products that have been rationalized accordingly.

Fastener Type

Lines 16 and 17 provide some insight into the relative influence of fastener selection. Eight penny (8d) ring shank (0.120-inch diameter) and 8d common (0.131-inch diameter) nails are assumed to provide equivalent performance for unblocked diaphragms in some prescriptive situations. The full-scale tests of Line 16 suggest that the smaller diameter ring shank nail actually out-performed the larger diameter common nail. Line 17 provides a similar comparison for a proprietary fastener that claims superior diaphragm performance for some configurations based on small-scale fastener testing and analysis. In reality, the proprietary fastener performed about the same as the smaller diameter ring shank nail. Extra withdrawal and lateral resistance doesn't necessarily translate into improved diaphragm performance if an alternative failure mode not addressed by the fastener review, such as framing splitting, governs. The designer should be cautious when specifying proprietary fasteners that claim diaphragm performance improvements that have not been verified against all failure modes possible in a full-scale diaphragm.

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Stiffness Observations

In some cases, a designer will also need to predict diaphragm deformation. For sawn lumber diaphragms, this is typically done using either the traditional "4-term" or simplified "3-term" diaphragm deflection equations.

Calculation procedures developed for sawn lumber diaphragms also provide a reasonable means of predicting I-joist diaphragm deformation in the design range. *Figure 5* illustrates a comparison between calculation methodologies and the measured behavior for a Case 5 I-joist diaphragm configuration that conservatively combined large diameter fasteners with a tight spacing that tends to promote splitting. For this example, observed performance reasonably approximated modeled deformation predictions based on the tested Case 5 configuration. It should be noted that the actual deformations are less than deformations predicted using the default apparent shear stiffness term in SDPWS. The SDPWS default is conservatively based on Case 1-4 diaphragm configurations which have fewer nails (e.g. greater load per nail) at panel edges than the Case 5 diaphragm configuration tested.

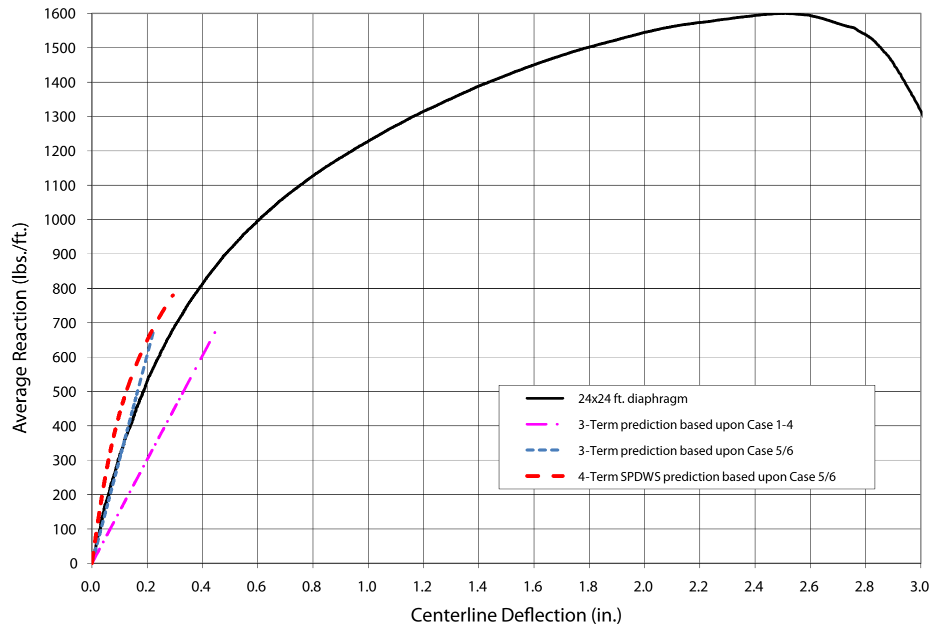

Figure 5: Deflection Predictions.

One of the benefits of testing diaphragms with a 1:1 aspect ratio is that it focuses the test on the shear strength and deformation of the assembly. A downside is that deflection measurements are small. For example, at a load and resistance factor load for the configuration illustrated, the disparity between the measured deformation and the Case 5 predictions was about 1⁄16 inch. This absolute differential arguably falls below the reasonable precision of the full scale test method, and highlights that the absolute magnitudes of deformation should be considered when interpreting the accuracy of a predictive model.

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Conclusions

Subject to the manufacturer's recommendations, pre-fabricated wood I-joists can be used for diaphragm construction. However, the performance of an I-joist diaphragm assembly will be dependent on specific I-joist product used and its relevant attributes (i.e. flange geometry, material, species, veneer thickness for LVL flanges, etc.). Few I-joists can serve as a direct substitute for sawn-lumber framing in the full range of applications addressed by building code diaphragm design provisions. The manufacturer's sheathing nail spacing and diaphragm design recommendations should always be considered as part of the design process.▪

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