THE INFLUENCE OF FOAM DISCONTINUITY IN THE SHEAR ZONE OF STRUCTURAL INSULATED PANEL BEAMS

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Abstract. The effect of foam discontinuity in the shear zone of structural insulated panel (SIP) beams was investigated in the current research. Two depths of 15.24 cm and 31.11 cm (6.5 in. and 12.25 in.) SIPs were evaluated in 1/3-point bending. Panels were sawn into beams, each approximately 29.84 cm (11.75 in.) wide, for the mechanical testing. Half of the panels had joints or discontinuities in the foam layer in a location that was subject to shear stress during the bending tests. Half of the panels did not have joints or discontinuities in the foam layer in the locations that were subject to shear stress during the bending tests. The specimens with no foam discontinuity, stressed in shear, were approximately twice as strong as the specimens with a foam discontinuity. This finding has implications for routine testing and evaluation as well as for allowable properties. In the case of routine testing, foam discontinuities should purposefully be located in the zone of maximum shear as these appear to be a limiting factor. In cases where a producer

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manufactures SIPs with zero discontinuities, it may be prudent to seek premium value as those panels would achieve superior properties.

Keywords: Structural insulated panels, shear stress, bending test, foam, joints, and routine testing.

INTRODUCTION

Structural insulated panels (SIPs) contain an insulating foam core sandwiched between two structural facings, typically oriented strand board (OSB). Other facing materials include plywood, gypsum sheathing, sheet metal, fiber cement siding, magnesium oxide board, fiberglass mat, and composite structural siding panels. The cores of SIPs are composed of foam products, expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane (PUR) (Morley 2000; Aldrich et al 2010).

SIPs are well established as a form of residential and light commercial building construction and widely used in both residential and nonresidential construction industries. They are extremely strong, energy-efficient, and cost-effective with excellent thermal resistance (Aldrich et al 2010; Cox and Hamel 2021). SIPs offer excellent energy performance as well as safe and reliable strength, stiffness, and other mechanical properties. Due to their superior thermal performance, decreased construction time and waste, and reducing carbon footprints, SIPs are increasingly becoming popular for commercial and residential construction in the United States and Canada (Morley 2000; Medina et al 2008; Mcintosh and Guthrie 2010). Although most SIPs are used in wall applications, they can also be used as roof or floor panels that are exposed to long-term transverse loading (McDonald et al 2014). With respect to building code compliance, SIPs are recognized by the International Residential Code. One of the properties that remains to be well investigated and modeled is load duration. The study detailed herein, related to static bending properties, is a component of a larger load duration study. Typically, during manufacturing, ridged foam insulation is sandwiched between matching layers of OSB facers. The ridged foam is commonly EPS, polyurethane, or XPS. The OSB facers are often full-length jumbo sheets (up to 7.31 m [24 ft.]) or end jointed (finger jointed or scarf jointed) 1.21 × 2.43 m (4 × 8 ft.) sheets. The foam core is bonded to the OSB facers with adhesives. In some cases, the foam may be the full length of the panel. In other cases, the foam may have end joints. These foam end joints act as discontinuities. These discontinuities have reduced shear capacity as compared with nonend jointed foam. While discontinuities in the foam are not necessarily randomly located, they are considered existent in the design and allowable properties. This consideration is prudent because a designer or engineer won't always know the extent to which a given SIP will have a discontinuity in a shear-critical area or application.

Creep or duration-of-load evaluation of SIPs follows ASTM D6815 (ASTM 2015b). Therein, the dead load values (and associated bending stress values) for the long-term "creep-rupture" or duration of load testing are based on laboratory short-term bending tests: "The specimens selected for these tests shall be tested at a constant stress level, f_b, … as determined in accordance with Eq 1 … where … $f_b = 0.55 \times (5\% \text{ PE})$ where f_b = minimum applied bending stress, and 5% PE = the lower five percent point estimate, as determined from the short-term bending tests … " In the case of the 30-specimen samples herein, the respective 5% parametric point estimates are determined as mean minus the standard deviation times 1.645. Testing is specified per either ASTM (2015a) or ASTM (2013). Each of those methods specifies full-scale flexural testing, ie testing in the structural size(s) in 1/3-point bending at a span: depth ratio ranging from 17:1 to 21:1.

Therefore, the objective of this research is to investigate the influence of foam discontinuities on the flexural performance of SIPs. It is hypothesized that the inclusion of a foam discontinuity in the area of maximum shear stress (locations between reaction supports and load head in a 1/3-point bending test) would significantly influence the flexural performance of the SIP beams.

MATERIALS AND METHODS

The research detailed herein occurred in three phases. Each phase used similarly specified SIP beams. Essentially, the beams had EPS foam cores, specified at a density of approximately 0.016 g/cm^3 (1.0 lb/ft.^{3}). All beams had 1.11-cm (7/16 in.) thick OSB facers. All OSB was the Engineered Wood Association (APA) rated, Exposure 1, 24/16 span rated. Test specimens were constructed with the OSB strength axis oriented parallel with the length of the SIP panel. Specimens were categorized into one of two depth classes, ie, either 15.24 cm and 31.11 cm (6.5 in. or 12.25 in.) deep. All specimens were approximately 29.84 cm (11.75 in.) wide. Specimens were tested in 1/3-point flexure at an approximate 18:1 span to depth ratio. As a target, half of the specimens had EPS foam with at least one discontinuity in the zone of maximum shear, ie between the reaction support and the load head; between zero and 1/3 of the span from the reaction support. Half of the specimens had EPS foam that did not have at least one discontinuity in the zone of maximum shear (Fig 1). Those specimens did have an EPS discontinuity, but it was located within the middle 1/3 of the span, ie the zone with zero shear stress.

As the first step in this evaluation (Study 1), a preliminary study was conducted and reported (McDonald et al 2014). There, 31.11-cm (12.25 in.) deep specimens were tested. The results of the bending tests are presented in McDonald et al (2014). These beams were tested in 1/3-point bending over a 5.48-m (18 ft. = 216 in.) long span (17.6:1 span: depth ratio). Summarized results from the short-term bending tests, with foam flush ends is shown in Table 1.

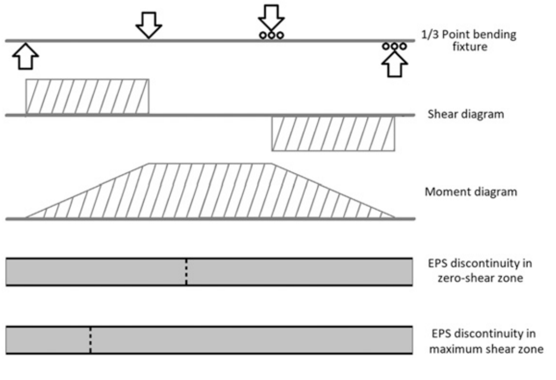

Figure 1. Diagram of 1/3 point flexural bending set up along with shear and moment diagrams, and sketch of expanded polystyrene (EPS) foam discontinuity location(s).

Also, the following information is footnoted to these results in that investigation: "Two failure modes were observed, each with a consistent strength value: Specimen that had adhesion failure failed near 5338 N (1,200 lbf). Specimen that had flange compression failed near 8896 N (2000 lbf)". Also, Figures 12 and 13 in McDonald et al (2014) illustrate the two failure modes: adhesion due to shear at EPS discontinuity and compression failure in the OSB, respectively. This study does not however discern which specimens had an EPS discontinuity in the zone of maximum shear and which do not. Next (Study 2), a full complement (28 specimens of each size) of 15.24 cm and 31.11 cm (6.5 in. deep and 12.25 in.) deep specimens were tested in bending (McDonald et al 2018). This number of specimens was selected because it is the minimum number from which a nonparametric 5th percentile can be computed. The 15.24-cm (6.5 in.) deep specimens were tested over a 300-cm (118.5 in.) long span (18.2 span: depth ratio). Similar to the previous work, the 31.11-cm (12.25 in.) deep specimens were tested over a 5.48-m (18 ft = 216 in.) long span

Table 1. Maximum load values for preliminary tests on 31.11 cm (12.25 in) deep SIPs beams.

Sample ID	P_{Max} (lbf)	P_{Max} (N)
13A	1237	5492.28
22A	1226	5443.44
23A	1264	5612.16
31A	1136	5043.84
38A	1232	5470.08
43A	1233	5474.52
1A	2011	8928.84
16A	2021	8973.24
24A	2109	9363.96
Average	1497	6645
StDev	415	1843
COV (%)	28	28

SIP, structural insulated panel.

(17.6 span: depth ratio). The maximum load values (P_{Max}) for those tests are shown in Table 2.

In general, these specimens each contained a discontinuity within the zone of maximum shear, in the EPS core. Appendix E in McDonald et al (2018) states that "the static bending tests typically failed in shear at the manufactured discontinuities in the EPS web. These discontinuities are points of dramatically decreased shear strength." As a comparison, for P_{Max} of the 31.11 cm (12.25 in.) deep specimens, the coefficients of variation (COV) for Study 1 and Study 2 were 28% and 7%, respectively. Study 1 listed two modes of failure (shear at EPS discontinuity and compression in OSB) whereas Study 2 listed only one mode of failure (shear at EPS discontinuity).

The third study (Study 3) was a generally a replication of Study 2 with the exception that none of the specimens contained an EPS discontinuity in the zone of maximum shear. These specimens were considered to be analogous to the stronger specimens that were noted in Study 1. In Study 3,

Table 2. Static bending (short term) test results for specimens which generally contained an EPS discontinuity within the zone of maximum shear.

15.24 cm (6.5 in) deep specimens			31.11 cm (12.25 in) deep specimens		
Specimen ID	P_{Max} (lbf)	P_{Max} (N)	Specimen ID	P_{Max} (lbf)	P_{Max} (N)
6-1	1154	5124	12-1	1017	4515
6-2	1179	5235	12-2	907	4027
6-3	1127	5004	12-3	1003	4453
6-4	1127	5004	12-4	873	3876
6-5	1029	4569	12-5	883	3921
6-6	1121	4977	12-6	902	4005
6-7	1137	5048	12-7	1022	4538
6-8	1072	4760	12-8	967	4293
6-9	1117	4959	12-9	941	4178
6-10	1016	4511	12-10	966	4289
6-11	1179	5235	12-11	918	4076
6-12	1054	4680	12-12	994	4413
6-13	1047	4649	12-13	1061	4711
6-14	1079	4791	12-14	1082	4804
6-15	1033	4587	12-15	1039	4613
6-16	997	4427	12-16	1062	4715
6-17	1000	4440	12-17	1079	4791
6-18	1001	4444	12-18	1086	4822
6-19	953	4231	12-19	1068	4742
6-20	955	4240	12-20	1069	4746
6-21	996	4422	12-21	1000	4440
6-22	981	4356	12-22	1081	4800
6-23	934	4147	12-23	1045	4640
6-24	909	4036	12-24	1093	4853
6-25	931	4134	12-25	1034	4591
6-26	911	4045	12-26	1065	4729
6-27	942	4182	12-27	1054	4680
6-28	909	4036	12-28	1069	4746
Average	1032	4581	Average	1014	4500
StDev	85.9	381.4	StDev	68.1	302.5
COV%	8	8	COV%	7	7
Nonparametric 5th percentile	909	4043	Nonparametric 5th percentile	873	3883
Parametric 5th percentile	871	3874	Parametric 5th percentile	886	3941

COV, coefficients of variation; EPS, expanded polystyrene.

Figure 2. Photos of the specimens before (a and b), during (c), and after testing (d and e).

another full complement (28 specimens of each thickness) of 15.24 cm and 31.11 cm depths (6.5 in. and 12.25 in.) specimens were tested in bending (Fig 2 [a-e]). The 15.24-cm (6.5 in.) deep specimens were tested over a 298.5-cm (117.5 in.) long span (18.2 span: depth ratio). Similar to the previous work (McDonald et al (2018)), the 31.11-cm (12.25 in.) deep specimens were tested over a 548.6-cm (18-ft = 216 in.) long span (17.6 span: depth ratio). The maximum load values (P_{Max}) for those tests are shown in Table 3.

STATISTICAL ANALYSIS

In this study, the experimental design was completely randomized design. Two-tailed t-tests, assuming equal variance, were used to compare the P_{Max} values. Additionally, all

Table 3. Static bending (short-term) test results for specimens that did not contain an EPS discontinuity within the zone of maximum shear.

15.24 cm (6.5 in) deep specimens			31.11 cm (12.25 in) deep specimens		
Specimen ID	P_{Max} (lbf)	P_{Max} (N)	Specimen ID	P_{Max} (lbf)	P_{Max} (N)
6-1	2082	9244	12-1	2644	11,739
6-2	2163	9604	12-2	2393	10,625
6-3	2136	9484	12-3	2524	11,207
6-4	2259	10,030	12-4	2584	11,473
6-5	2119	9408	12-5	2554	11,340
6-6	2123	9426	12-6	2578	11,446
6-7	2123	9426	12-7	2562	11,375
6-8	2171	9639	12-8	2641	11,726
6-9	2247	9977	12-9	2665	11,833
6-10	2166	9617	12-10	2362	10,487
6-11	2024	8987	12-11	2726	12,103
6-12	2126	9439	12-12	2289	10,163
6-13	2101	9328	12-13	2477	10,998
6-14	2216	9839	12-14	2511	11,149
6-15	2220	9857	12-15	2512	11,153
6-16	2156	9573	12-16	2442	10,842
6-17	2116	9395	12-18	2217	9843
6-18	2175	9657	12-19	2408	10,692
6-19	2174	9653	12-20	2547	11,309
6-20	2060	9146	12-21	2591	11,504
6-21	2143	9515	12-22	2584	11,473
6-22	2281	10,128	12-23	2800	12,432
6-23	2245	9968	12-24	2417	10,731
6-24	2257	10,021	12-25	2702	11,997
6-25	2096	9306	12-26	2434	10,807
6-26	2248	9981	12-27	2659	11,806
6-27	2196	9750	12-28	2757	12,241
6-28	2312	10,265	12-29	2614	11,606
Average	2169	9631	Average	2543	11,289
StDev	71	316	StDev	139	616
COV%	3	3	COV%	5	5
Nonparametric 5th percentile	2024	9003	Nonparametric 5th percentile	2217	9861
Parametric 5th percentile	2036	9656	Parametric 5th percentile	2283	10,155

COV, coefficients of variation; EPS, expanded polystyrene.

P_{Max} values within the 15.24 cm and 31.11 cm (6.5 in and 12.25 in.) depths sizes from Study 2 (with EPS discontinuity in zone of maximum shear) and Study 3 (without EPS discontinuity in zone of maximum shear) were analyzed by analysis of variance (ANOVA) using the procedure for general linear mixed models (PROC GLIMMIX) of SAS 9.4 (Statistical Analysis System [SAS] Institute 2013). Differences were deemed significant at $p \leq 0.05$.

RESULTS AND DISCUSSIONS

The cumulative frequencies of the 15.24 cm and 31.11 cm (6.5 in. and 12.25 in.) depths, have been illustrated in Figs 3 and 4, respectively. These charts indicate that within each depth, there appears to be a bimodal frequency distribution stemming from the two different failure modes.

Two-tailed *t*-tests were used to compare the P_{Max} values within the 15.24 cm and 31.11 cm (6.5 in and 12.25 in.) depths sizes from Study 2 (with

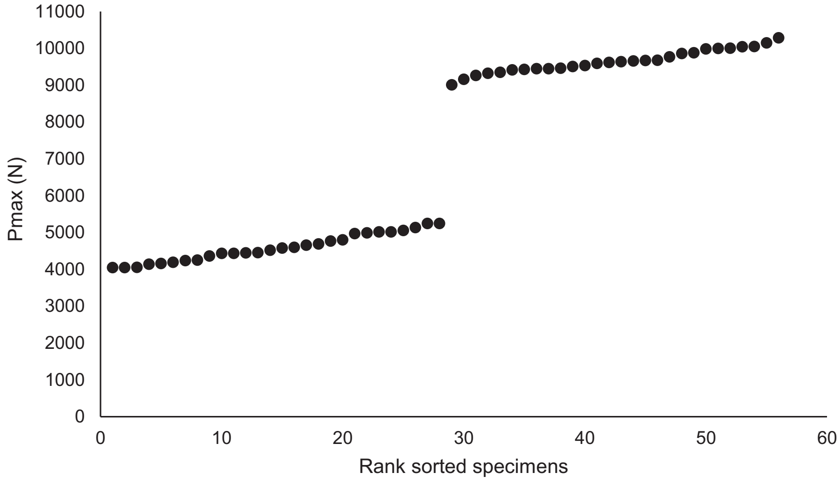

Figure 3. Cumulative frequency distribution chart for the 15.24 cm (6.5 in) deep structural insulated panel (SIP) beams.

EPS discontinuity in zone of maximum shear) and Study 3 (without EPS discontinuity in zone of maximum shear). It was possible to compare P_{Max} values directly because specimen sizes and test-machine set ups were comparable for both Study 2 and Study 3. The summary statistic comparing the flexural strength of beams with and without EPS discontinuities in the zone of maximum shear within each of the two thicknesses, which is shown in Tables 4 and 5 illustrates the summary statistics of the pooled data (from both beams with and without EPS discontinuities in the maximum shear zone) for each of the two thicknesses.

The results of ANOVA analysis have been shown in Tables 6 and 7. According to the results of Tables 6 and 7, there was significant differences between with and without EPS discontinuity and between EPS discontinuity and depth of the specimens.

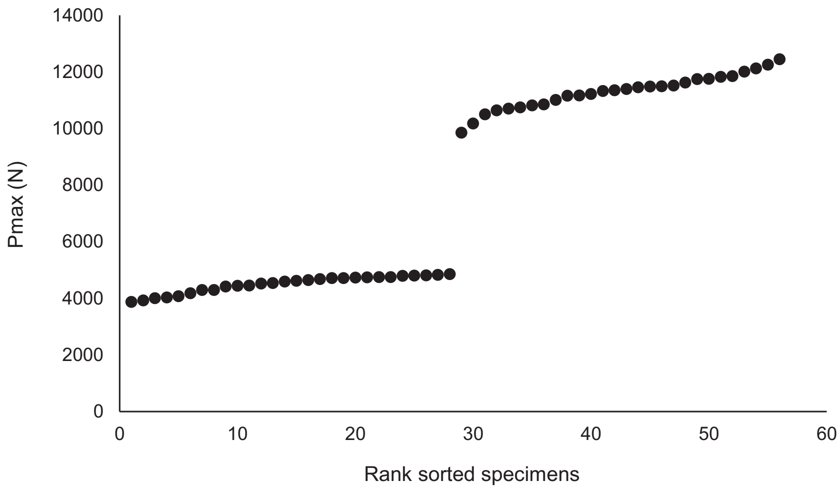

Figure 4. Cumulative frequency distribution chart for the 31.11 cm (12.25 in) deep structural insulated panel (SIP) beams.

Table 4. P_{Max} (N and lbf) summary statistics for the specimens either with or without EPS discontinuities in each size. N for each group is 28.

Depth cm (in)	EPS discontinuity	Mean N (lbf)	Nonparametric 5th percentile N (lbf)	Parametric 5th percentile N (lbf)	COV%	p value from t-tests
15.24 (6.5)	With	4590 (1032)	4043 (909)	3874 (871)	8	5.63 × 10-49
15.24 (6.5)	Without	9648 (2169)	9003 (2024)	9056 (2036)	3	
31.11 (12.25)	With	4510 (1014)	3883 (873)	3941 (886)	7	5.04 × 10-31
31.11 (12.25)	Without	11,311 (2543)	9861 (2217)	10,155 (2283)	5	

EPS, expanded polystyrene.

As it was hypothesized, for each thickness 15.24 cm and 31.11 cm (6.5 in. and 12.25 in.), statistically significant differences were detected by the t-test between specimens with an EPS discontinuity in the zone of maximum shear vs specimens without an EPS discontinuity. In the case where the EPS discontinuity is considered and specimens are separated, the parametric and nonparametric 5th percentiles are similar. This finding suggests that the data are not skewed in either direction about the mean. In the case where this discontinuity is considered and specimens are thereby separated, their respective COV values for P_{Max} are relatively low and on the order of 5-7%. In the case where this type of discontinuity is not considered and specimens are pooled, their respective COV values are relatively high and on the order of 40%. This finding suggests that these two very different failure modes create a bimodal distribution of strength data with one mode (OSB compression) developing strength levels approximately two times the other mode (shear critical). Figures 3 and 4 support this conclusion. This issue becomes particularly punitive if the parametric 5th percentile were to be used to calculate design strength and moment capacity because the relatively high variability produces a relatively low 5th percentile, which directly leads to a relatively low allowable capacity. This finding suggests that when SIPS are testing in 1/3-point bending, it is prudent to purposefully include at least one discontinuity in the foam in the zone of maximum shear. This finding also suggests that should a manufacturer produce SIPs with no discontinuities in the foam then their product would likely develop superior design values.

CONCLUSIONS

The effect of foam discontinuity in the shear zone of SIP beams was investigated in the current research. The results of EPS discontinuity showed that the specimens with no foam discontinuity had more strength in comparison with the specimens with a foam discontinuity. This finding has implications for routine testing and evaluation as well as for allowable properties. It should be considered that in the case of routine testing, foam discontinuities should purposefully be located in the zone of maximum shear as these appear to be a limiting factor. In cases where a producer manufactures SIPs with zero discontinuities, it may be prudent to seek premium value as those panels

Table 5. P_{Max} (N and lbf) summary statistics for the pooled specimens, both with and without EPS discontinuities in each size.

	Mean N (lbf)	Nonparametric 5th percentile N (lbf)	Parametric 5th percentile N (lbf)	COV%
6.5-inch-deep, pooled, both with and without EPS discontinuity	7117 (1600)	4043 (909)	2482 (558)	36
12.25-inch-deep, pooled, both with and without EPS discontinuity	7909 (1778)	3928 (883)	1672 (376)	44

EPS, expanded polystyrene.

Table 6. Mean P_{Max} (N) along with p value levels of significance as well as mean separations. Materials with the same letter were not statistically different from each other at 0.05 level of significance.

EPS discontinuity	Depth of specimens: 15.24 cm (6.5 in)	Depth of specimens: 31.11 cm (12.25 in)
	P_{Max} (N)	P_{Max} (N)
With	4581^b	4500^b
Without	9631^a	$11,289^a$
SEM	93.5	91.7
p value	<0.0001	<0.0001

would achieve superior properties. Also, if producers wish to seek premium or high-grade products, they might also apply adhesive to the foam discontinuities at the time of manufacture, thereby reducing or eliminating the reductions in strength associated therewith.

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Table 7. P_{max} (N) values with and without EPS discontinuities in each size along with p value levels of significance as well as mean separations (materials with the same letter were not statistically different from each other at the alpha = 0.05 level of significance).

EPS discontinuity	Depth of specimens	P_{Max} (N)
With	15.24 cm (6.5 in)	4581^c
Without	15.24 cm (6.5 in)	9631^b
With	31.11 cm (12.25 in)	4500^c
Without	31.11 cm (12.25 in)	$11,289^a$
Pooled SEM		80.0
p value	EPS discontinuity	<0.0001
	Depth	<0.0001
	EPS discontinuity × Depth	<0.0001

EPS, expanded polystyrene.

REFERENCES

Aldrich RA, Arena L, Zoeller W (2010) Practical residential wall systems: R-30 and beyond *in* Proceedings of Building Enclosure Science & Technology (BEST2) Conference, National Institute of Building Sciences, Washington, DC.

American Society of Testing and Materials (ASTM) (2015a) Standard test methods of static tests of lumber in structural sizes. American Society of Testing and Materials, West Conshohocken, PA. ASTM D198-15.

American Society of Testing and Materials (ASTM) (2013) Standard test methods for mechanical properties of lumber and wood-base structural material. American Society of Testing and Materials. ASTM D4761-13. ASTM, West Conshohocken, PA.

American Society of Testing and Materials (ASTM) (2015b) ASTM, West Conshohocken, PA.

American Society of Testing and Materials (ASTM) (2015b) Standard specification for evaluation of duration of load and creep effects of wood and wood-based products. ASTM D6815-15. ASTM, West Conshohocken, PA.

Cox NI, Hamel SE (2021) Static modeling of plywood–polyurethane structural insulated panels in bending. J Struct Eng 147(2):04020334.

McDonald D, Begal M, Senalik CA, Ross R, Skaggs TD, Yeh B, Williamson T 2014. Creep behavior of structural insulated panels (SIPs): Results from a pilot study. Research Note FPL-RN-0332. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 12 pp.

McDonald DE, Begel M, Senalik CA, Williamson T (2018) Evaluation of creep performance of structural insulated panels (SIPs): Phase 2. Research Paper FPL-RP-697. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 12 pp.

Mcintosh J, Guthrie C (2010) Structural insulated panels: A sustainable option for house construction in New Zealand. Int. J. Hous. Sci. 34(1):1-13.

Medina MA, King JB, Zhang M (2008) On the heat transfer rate reduction of structural insulated panels (SIPs) outfitted with phase change materials (PCMs). Energy 33(4):667-678.

Morley M 2000. Structural insulated panels: Strength and energy efficiency through structural panel construction. Taunton Press, Newton, CT.

Statistical Analysis System (SAS) Institute (2013) User guide: Statistics (Release 9.4). SAS Institute, Cary, NC.