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COMPOSITE ACTION OF I-JOIST FLOOR SYSTEMS

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Composite Action of I-Joist Floor Systems

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Abstract

In 1968, APA conducted field-glued plywood-joist floor system tests and established floor composite action factors based on the research results that have subsequently been in use in the United States for 40 years. Those composite action factors were based on the use of a single layer plywood floor (underlayment) glue-nailed to sawn lumber joist systems to improve the stiffness of the floor and to minimize the impact of nail pull-out and associated squeaks. Prefabricated wood I-joists, while having been used in the United States and Canada for over 30 years, are now gaining acceptance in Europe and other geographic regions such as Australasia for residential floor construction. In fact, approximately 45% of all raised wood floors constructed in North America now use I-joists which represent over 300 million lineal meters (984 x 10^6 lineal feet).

As a result, APA recently conducted a study to review the effect of glue-nailed assemblies on the stiffness capacity of I-joist floor systems with oriented strand board (OSB) floor sheathing since OSB is widely used in residential floor construction today. Bending tests on full scale-floor sections as well as T-beam sections with panels glue-nailed to the I-joist frame were conducted. Based on this research, a new composite action factor for glue-nailed I-joist floor systems was established.

APA also conducted an intensive testing program to assess the EA-perpendicular (axial stiffness) properties for OSB. An impact study was then conducted to investigate the effect of this new composite action factor on the allowable spans of I-joist floor systems when the axial stiffness of OSB floor sheathing in the direction perpendicular to the strength axis of the panel is reduced, as evidenced by these recent tests conducted by APA. This paper presents the results of these studies and provides recommendations for determining the spans of wood I-joists used in floor systems.

1. Introduction

Wood floors made of wood structural panel sheathing that is glue-nailed to wood joists are much stiffer than the stiffness of the wood joists alone. This phenomenon is attributed to the floor composite action and has been studied by several researchers, as summarized in the APA Laboratory Report LR-118 [1] and USDA Forest Products Laboratory Research Paper RP-289 [2]. As part of the APA LR-118, floor composite action factors for field-glued plywood-lumber joist floor systems were established. These same composite action factors have been adopted by the engineered products industry and the wood engineering community in the United States for 40 years.

According to the APA LR-118, the composite action factor, C, is defined in Equation 1. For floor systems with the floor sheathing glue-nailed to floor joists, C is equal to 0.90 if the tongue-and-groove (T&G) of the floor sheathing is also glued. Otherwise C is equal to 0.45 if the T&G of the floor sheathing is nailed only. For floor systems with the floor sheathing nailed to floor joists without gluing, it is assumed that there is no composite action, i.e., C is equal to 0.

$$C = \frac{\text{Actual \% increase in stiffness}}{\text{\% increase if fully composite}} = \frac{\frac{EI_{effective}}{EI_{joist}} - 1}{\frac{EI_{composite}}{EI_{joist}} - 1} \tag{1}$$

where $EI_{composite}$ = bending stiffness of the fully composite floor and
EI_{joist} = bending stiffness of the floor joists alone
C = composite action factor

The composite action factors established in APA LR-118 were based on the use of a single layer plywood floor (underlayment) glue-nailed to sawn lumber joist systems to improve the stiffness of the floor and to minimize the impact of nail pull-out and associated squeaks. Prefabricated wood I-joists, while having been used in the U.S. and Canada for over 30 years, are now gaining acceptance in Europe and other geographic regions such as Australasia for residential floor construction. In fact, approximately 45% of all raised wood floors constructed in North America now use I-joists which represent over 300 million lineal meters (984 x 10^6 lineal feet).

The wood I-joist industry has adopted the use of Equation 1 when calculating the allowable floor spans that are often governed by the live load deflection criterion of L/480, where L is the on-center floor span. This live load deflection criterion is more stringent than the code-specified L/360 and represents a voluntary standard adopted by the wood I-joist industry in the U.S. As a result, the composite action factor is an essential part of the allowable floor spans recommended by the wood I-joist manufacturers. As there have been no industry-wide data based on wood I-joist floor systems to confirm the composite action factors recommended in APA LR-118, APA recently conducted a study to review the effect of glue-nailed assemblies on the stiffness capacity of I-joist floor systems with oriented strand board (OSB) floor sheathing since OSB is widely used in residential floor construction today. This paper provides the test results and analyses.

2. Materials and Test Methods

2.1 Material Description

Table 1 provides the test matrix and materials used in this study. All materials were purchased locally in Tacoma, Washington, and were tested in the as-received conditions. The OSB floor sheathing contained T&G and had a nominal thickness of 15 mm (19/32 in.) meeting the requirements of a single floor 20 oc span rating in accordance with Voluntary Product Standard PS2 [3]. The wood I-joists were 241 mm (9-1/2 in.) in depth meeting the requirements of APA PRI-400, *Performance Standard for APA EWS I-Joists* [4]. To cover a range of manufacturing variables, two I-joist series were tested. The PRI-30 series I-joists used 33 x 38 mm (1-5/16 x 1-1/2 in.) laminated veneer (LVL) flanges and 9.5 mm (3/8 in.) OSB web oriented vertically (i.e., the strength axis is perpendicular to the length of the I-joist). The PRI-40 series I-joists used 38 x 64 mm (1-1/2 x 2-1/2 in.) spruce-pine-fir (SPF) lumber flanges and 9.5 mm (3/8 in.) OSB web oriented vertically. These I-joist series represent the smallest sizes of LVL and lumber flanges typically used in North America and it is expected that the floor composite action factors determined from this study can be conservatively applied to other I-joist floor systems with larger flange sizes and deeper I-joists.

Table 1. Numbers of specimens and test matrix

Floor Sheathing	I-joist	Floor Assembly			T-Beam	
		Individual I-joist EI	Bare I-joist Frame Assembly	Complete Assembly[(a)]	Individual I-joist EI	Complete T-beam[(a)]
15 mm (19/32 in.) OSB Floor Sheathing 20 oc, T&G	241 mm (9-1/2 in.) I-joists with 33 x 38 mm (1-5/16 x 1-1/2 in.) LVL Flange (PRI-30)	6	2	2	2	2
	241 mm (9-1/2 in.) I-joists with 38 x 64 mm (1-1/2 x 2-1/2 in.) SPF Lumber Flange (PRI-40)	6	2	2	2	2

[(a)] With the glue-nailed OSB floor sheathing installed.

The adhesive used to fabricate the T-beam and floor assembly was a commercially available elastomeric construction adhesive (Liquid Nails) meeting ASTM D 3498, *Standard Specification for Adhesives for Field-Gluing Plywood to Lumber Framing for Floor Systems* [5]. Details for the assembly preparation are provided in the following sections.

2.2 Test Methods

2.2.1 General

Prior to assembly tests, the EI and EA of the floor sheathing and the EI of individual I-joist were non-destructively tested. The sheathing and I-joists were sorted into different groups based on the material EI. The T-beams, I-joist frames, and floor assemblies were then fabricated by laboratory technicians according to the test matrix shown in Table 1.

2.2.2 Panel EI and EA Tests

OSB sheathing EI in the across-panel direction was non-destructively tested in accordance with Method C – Pure Moment of ASTM D 3043, *Standard Test Methods for Structural Panels in Flexure* [6]. OSB sheathing EA in the across-panel direction was non-destructively tested based on ASTM D 3501, *Standard Test Methods for Wood-Based Structural Panels in Compression* [7]. This loading direction matches the common construction practice of residential floors in North America where the floor sheathing is typically installed with the sheathing strength axis perpendicular to the supporting I-joists.

2.2.3 Individual I-Joist EI Tests

The third-point bending test method of ASTM D 198, *Standard Test Methods of Static Tests of Lumber in Structural Sizes* [8], was used for the non-destructive I-joist EI tests. The on-center test span was 4572 mm (180 in.) and the maximum load was limited to 6.7 kN (1,500 lbf) to avoid any damages to the I-joists.

2.2.4 I-Joist Frame Assembly Tests

I-joist frames without floor sheathing, as shown in Figure 1, were installed following the APA recommendation for I-joist floor installation as specified in *APA Performance Rated I-Joists* [9]. OSB rim boards meeting the requirements of APA PRR-401, *Performance Standard for APA EWS Rim Boards* [10], were nailed to the end of I-joists using one 8d common nail (3.3 x 64 mm or 0.131 x 2-1/2 in.) at the top and bottom flanges. Three I-joists that had the closest EI values were grouped to frame an I-joist assembly with a spacing of 406 mm (16 in.) on center. Each "bare frame assembly" was tested to obtain EI values for the bare I-joist frame. For a given assembly, the bare I-joist frame EI was divided by 3 to represent EI_{joist} used in the composite action factor analysis.

Figure 1. Test setup for bare I-joist frames

2.2.5 I-Joist Floor Assembly Tests

After the bare I-joist frame tests were completed, the 15-mm (19/32-in.) OSB floor sheathing that had been non-destructively tested was installed with the strength axis perpendicular to the supporting I-joists, as shown in Figure 2. A single 6.4-mm- (1/4-in.-) diameter bead of elastomeric construction adhesive meeting ASTM D 3498 was applied to the joists and rim boards. Two lines of adhesive were applied to I-joists where panel ends butt to assure proper gluing of each end. Eight-penny (8d) common nails (3.3 x 64 mm or 0.131 x 2-1/2 in.) were used to install the floor sheathing to the I-joists with a 152 mm (6 in.) spacing on the edges and 305 mm (12 in.) spacing in the field. A 3.2 mm (1/8 in.) gap was left between all panel edge joints in accordance with industry installation recommendations. Adhesive was not applied to the T&G of the floor sheathing. The floor assemblies were stored in the laboratory under an indoor environment (approximately 15-18^{O}C or 60-65^{O}F and 50% RH) for at least 10 days prior to testing. For a given floor assembly, the I-joist floor assembly EI was divided by 3 to represent $EI_{effective}$ used in the composite action factor analysis.

Figure 2. Test setup for I-joist floor assemblies

2.2.6 T-Beam Assembly Tests

T-beam assemblies were fabricated following the same installation details as specified for I-joist floor assemblies except that the width of the OSB was 406 mm (16 in.), as shown in Figure 3. The T-beams were stored in the laboratory under an indoor environment for at least 10 days prior to testing. For a given T-beam assembly, the assembly EI represents $EI_{effective}$ used in the composite action factor analysis.

Figure 3. Test setup for T-beam assemblies

2.2.7 Assembly Tests Methods

The third-point bending test method of ASTM D 198 was used for non-destructive testing of (a) each bare I-joist frame (without the OSB floor sheathing installed), (b) the I-joist floor assembly (with the OSB floor sheathing installed), and (c) the T-beam assemblies. The on-center test span was 4572 mm (180 in.). Lateral supports were provided for the T-beam assemblies. The deflection at the mid-span of each I-joist at its neutral axis was measured. The deflection at the two ends of the center I-joist was also measured and subtracted from the measured mid-span deflection. For all assembly tests, a test load equivalent to the floor load of 2.4 kPa (50 lbf/ft^2) was applied at a loading rate of 12.7 mm/min (0.5 in./min). Three tests were repeated for each assembly with an approximate 3-min recovery interval between tests. The average of the three repeated tests was reported for each assembly.

3. Results and Discussions

Test results and the derived construction factors are summarized in Table 2. The $EI_{effective}$ values obtained from the floor assembly tests (F30 and F40) are in good agreement with the values measured directly from the T-beam tests (T-30 and T-40). With the EI_{joist} determined from individual I-joist EI tests (see Section 2.2.3) and sheathing $EI_{\perp}$ and $EA_{\perp}$ properties determined from panel tests (see Section 2.2.2), the $EI_{composite}$ can be calculated using the principle of engineering mechanics, as demonstrated in APA LR-118. Again, the calculated $EI_{composite}$ values are in good agreement between the floor assembly tests (F30 and F40) and the T-beam tests (T-30 and T-40).

Finally, the composite action factor, C, can be determined in accordance with Equation 1 using the values of EI_{joist}, $EI_{effective}$, and $EI_{composite}$. As can be seen from Table 2, the average floor composite factor determined from this study (based on floor assembly test results only) is equal to 0.57 for glue-nailed I-joist floor systems with unglued T&G.

Table 2. Summary of test results

Test[(a)]	I-Joist Properties			15 mm (19/32 in.) OSB Properties				$EI_{effective}$[(d)] (10^6 lbf-in.^{2})	$EI_{composite}$[(e)] (10^6 lbf-in.^{2})	C[(f)]
	A[(a)] (in.^{2})	I[(b)] (in.^{4})	EI_{joist}[(c)] (10^6 lbf-in^2)	Thickness (in.)	A (in.^{2}/ft)	$EA_{\perp}$ (10^6 lbf/ft)	$EI_{\perp}$ (10^3 lbf-in.^{2}/ft)			
F30-1	5.31	72.0	146	0.608	7.295	3.87	0.100	189	235	0.48
F30-2			140	0.610	7.324	3.95	0.103	188	229	0.53
F40-1	8.80	126.0	167	0.607	7.279	3.57	0.093	235	253	0.79
F40-2			184	0.607	7.287	3.81	0.095	227	277	0.46
T30-1	5.31	72.0	147	0.609	7.302	3.79	0.094	188	235	0.47
T30-2			153	0.610	7.326	3.47	0.081	197	237	0.52
T40-1	8.80	126.0	161	0.609	7.310	3,50	0.092	217	246	0.66
T40-2			159	0.607	7.283	4.00	0.099	224	251	0.71
Average (All)										0.58
Average (4 Floor Assemblies)										0.57
Average (4 T-beams)										0.59

For SI: 1 lbf = 4.448 N; 1 in. = 25.4 mm; 1 ft = 304.8 mm

(a) F30 and F40 are the I-joist floor assemblies with PRI-30 PRI-40 I-joists (see Table 1), respectively. Two replicates were tested, which are denoted as 1 and 2 in the last digit of the test number. T30 and T40 are the T-beam assemblies with PRI-30 and PRI-40 I-joists, respectively.
(b) Nominal I-joist cross section (A) and moment of inertia (I) are based on a 0.20-in. (5 mm) transformed web thickness.
(c) For F30 and F40, I-joist EI is based on the average of 3 I-joists from the respective bare I-joist frame test without the OSB floor sheathing.
(d) For F30 and F40, effective floor EI is based on the average of 3 I-joists from the respective I-joist floor assembly test with the glue-nailed OSB floor sheathing installed.
(e) Composite floor EI is calculated based on the I-joist and sheathing properties tabulated in this table.
(f) The floor composite action factor (C) is determined based on Equation 1.

3.1 Discussion

While the data provided from this study is relatively limited, the increase in the composite action factor for I-joist floor systems is not unexpected due to consistent product quality for I-joists, as compared to sawn lumber joists. In addition, it is likely that the better adhesive technology available today, as compared to 40 years ago when APA LR-118 was studied, provides a more efficient mechanism for the development of the composite action for I-joist floor systems.

The effect of the increased composite action factor from the existing 0.45 to 0.55 (rounded down from 0.57) on the allowable I-joist spans is shown in Table 3 for simple-span applications and Table 4 for multiple-span applications using the I-joist properties published in the APA PRI-400 I-joist standard for residential floor construction. The effective EI of an I-joist floor system is calculated based on Equation 2, which is rearranged from Equation 1.

$$EI_{effective} = (C)\ EI_{composite} + (1 - C)\ EI_{joist} \qquad (2)$$

Table 3. Effect of increased composite action factor from 0.45 to 0.55 (simple-span)

I-Joist Series	Allowable Clear Span (mm) for Simple-Span Application[a]				Difference (mm)	
	C = 0.45		C = 0.55			
	On-Center Joist Spacing					
	406 mm (16 in.)	610 mm (24 in.)	406 mm (16 in.)	610 mm (24 in.)	406 mm (16 in.)	610 mm (24 in.)
9-1/2" PRI-20	4623	4089	4699	4166	76	76
9-1/2" PRI-30	4775	4216	4851	4293	76	76
9-1/2" PRI-40	5004	4420	5080	4470	76	51
9-1/2" PRI-50	4978	4394	5029	4470	51	76
9-1/2" PRI-60	5283	4648	5334	4724	51	76
11-7/8" PRI-20	5537	4877	5613	4877	76	0
11-7/8" PRI-30	5715	5029	5791	5131	76	102
11-7/8" PRI-40	5969	5080	6045	5080	76	0
11-7/8" PRI-50	5944	5232	6020	5309	76	76
11-7/8" PRI-60	6299	5537	6375	5613	76	76
11-7/8" PRI-70	6401	5639	6477	5715	76	76
11-7/8" PRI-80	6909	6045	6960	6121	51	76
11-7/8" PRI-90	7112	6223	7163	6299	51	76
14" PRI-40	6782	5588	6858	5588	76	0
14" PRI-50	6756	5969	6858	6045	102	76
14" PRI-60	7163	6299	7239	6375	76	76
14" PRI-70	7264	6375	7341	6477	76	102
14" PRI-80	7849	6883	7899	6960	51	76
14" PRI-90	8052	7061	8128	7137	76	76
16" PRI-40	7391	6020	7391	6020	0	0
16" PRI-50	7518	6147	7620	6147	102	0
16" PRI-60	7925	6960	8026	7061	102	102
16" PRI-70	8052	7036	8128	7036	76	0
16" PRI-80	8687	7620	8763	7696	76	76
16" PRI-90	8915	7798	8992	7899	76	102

[a] Based on the live load deflection criterion of L/480, where L is the on-center span

Table 4. Effect of increased composite action factor from 0.45 to 0.55 (multiple-span)

I-Joist Series	Allowable Clear Span (mm) for Multiple-Span Application[(a)]				Difference (mm)	
	C = 0.45		C = 0.55			
	On-Center Joist Spacing					
	406 mm (16 in.)	610 mm (24 in.)	406 mm (16 in.)	610 mm (24 in.)	406 mm (16 in.)	610 mm (24 in.)
9-1/2" PRI-20	5029	4089	5105	4089	76	0
9-1/2" PRI-30	5182	4572	5283	4572	102	0
9-1/2" PRI-40	5461	4445	5461	4445	0	0
9-1/2" PRI-50	5410	4750	5486	4851	76	102
9-1/2" PRI-60	5740	5029	5817	5131	76	102
11-7/8" PRI-20	5969	4089	5969	4089	0	0
11-7/8" PRI-30	6223	4572	6299	4572	76	0
11-7/8" PRI-40	6223	5055	6223	5055	0	0
11-7/8" PRI-50	6452	4902	6553	4902	102	0
11-7/8" PRI-60	6858	5969	6934	5969	76	0
11-7/8" PRI-70	6960	5639	7036	5639	76	0
11-7/8" PRI-80	7518	6579	7595	6655	76	76
11-7/8" PRI-90	7747	6756	7798	6833	51	76
14" PRI-40	6833	5563	6833	5563	0	0
14" PRI-50	7366	4902	7391	4902	25	0
14" PRI-60	7798	6020	7874	6020	76	0
14" PRI-70	7899	5639	7976	5639	76	0
14" PRI-80	8534	7290	8611	7290	76	0
14" PRI-90	8788	7671	8839	7747	51	76
16" PRI-40	7366	5994	7366	5994	0	0
16" PRI-50	7391	4902	7391	4902	0	0
16" PRI-60	8636	6020	8661	6020	25	0
16" PRI-70	8484	5639	8484	5639	0	0
16" PRI-80	9474	7290	9550	7290	76	0
16" PRI-90	9703	8103	9779	8103	76	0

[(a)] Based on the live load deflection criterion of L/480, where L is the on-center span

As seen from Tables 3 and 4, the increase in the composite action factor from 0.45 to 0.55 increases the allowable spans up to 102 mm (4 in.) in some cases. Those cases showing no increase in the allowable spans are those governed by moment, reaction, or shear capacities of the I-joist. The most significant increases are for simple span applications as would be expected as these are often controlled by deflection. While these relatively small increases in allowable spans may seem insignificant in most engineered applications, I-joists are very competitive with commodity products, such as sawn lumber or parallel chord trusses, in the North American marketplace and this increase is considered positive to the wood I-joist industry as a whole.

Note that the allowable spans shown in Tables 3 and 4 are affected by the properties of floor sheathing, especially $EA_{\perp}$. In recent years, the allowable $EA_{\perp}$ value for OSB sheathing has declined significantly due to a variety of reasons. For example, based on an extensive quarterly test program administered by APA, the design $EA_{\perp}$ value for 15-mm (19/32-in.) OSB floor sheathing that is typically used for the joist spacing of 488 mm (19.2 in.) or less has recently been reduced in the APA *Panel Design Specification* (PDS) [11] from 65660 kN/m (4.5×10^6 lbf/ft) to 42300 kN/m (2.9×10^6 lbf/ft), a 35% reduction. Similarly, the design $EA_{\perp}$ value for 18-mm (23/32-in.) OSB floor sheathing that is typically used for the joist spacing of 610 mm (24 in.) or less has also been reduced from 65660 kN/m (4.5×10^6 lbf/ft) to 48100 kN/m (3.3×10^6 lbf/ft), a 27% reduction.

These reduced $EA_{\perp}$ values for OSB floor sheathing have a negative effect on the allowable I-joist spans by as much as 127 mm (5 in.). Therefore, the combined effect between the increase in the composite action factor and the reduction in the OSB $EA_{\perp}$ values essentially offset each other. Considering the fact that the actual EI of I-joists manufactured in North America is usually 5 to 7% higher than the published EI values [12], it is believed that the I-joist floor systems designed to the existing allowable spans remain adequate for the intended purposes. This is consistent with filed experience in North America of I-joist floor systems since no obvious problems have been reported due to excessive I-joist floor deflection. Therefore, the wood I-joist industry has recommended no change to the existing allowable spans and the analytical procedures used to determine the composite floor stiffness.

4. Conclusions and Recommendations

Results obtained from this limited study confirm that the composite action factor currently used by the wood I-joist industry in the U.S. is conservative. A composite action factor of 0.55 seems justifiable for glue-nailed I-joist floor systems with unglued T&G. While these results are rational and as expected, additional floor assembly tests may be considered in the future to expand the database and gain more confidence in the results.

The increase in the composite action factor results in an increase of the I-joist floor spans in residential floor applications up to 102 mm (4 in.). However, this increase needs to be considered in conjunction with other factors contributing to the composite floor stiffness, such as the recent reduction in the $EA_{\perp}$ design value of OSB floor sheathing. The net effect supports the recommendation of the North American wood I-joist industry that no changes to the existing allowable spans are required. However, if other factors that contribute to the composite floor stiffness are changed in the future, the I-joist spans need to be re-evaluated, including the composite action factors.

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