Investigation of the Role of Shear Deflection in the Flexural Performance of Structural Insulated Panels

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Abstract

As a material used in building construction, structural insulated panels (SIPs) deflect under flexural loading and creep over time. This work examines the deflection behavior of full-scale SIPs that were tested in bending. Approximately half of the matched specimens were tested after production and the other half were tested after a 90-day creep test. Of primary interest was the deflection behavior of the SIPs under load. After testing, the deflection was apportioned between the bending stiffness of the oriented strand board (OSB) and the shear modulus of the foam. Results indicated that when the known OSB modulus of elasticity values of 664,000 psi and 931,000 psi were considered among the different SIP thickness and treatments (with and without creep testing), the shear-based deflection from the foam ranged from 44 to 73 percent of the overall deflection. The calculated foam modulus of rigidity decreased slightly but significantly after creep testing. Also, the shear-based foam deflection increased slightly but significantly after creep testing.

Shear Deformation

Wood-based beam deflection is generally comprised of two components: that from bending and that from shear. Early work in this area of wood materials science was critical to understanding the behavior of wood composite airplane wings under load (Newlin and Trayer 1956). Newlin and Trayer (1956) stated, "By neglecting the deformation due to shear, errors of considerable magnitude may be introduced in determining the distortion of a beam, especially if it is relatively short, or has comparatively thin webs as the box or I-beams commonly used in airplane construction."

Biblis (1965) added that this concept is also true for laminated beams of two species where the denser species forms the faces and the less dense species forms the core. In that case, the less dense species, with lesser modulus of rigidity (*G*, also known as shear modulus) is located in the zone where shear stresses are maximized. Biblis (1965) concluded his work with the statement "it can be concluded that the shear influence on the deflection of wood beams can be considerable, approaching or even exceeding the amount of deflection due to pure bending." The magnitude of shear deflection depends on the span-to-depth ratio of the beam and also on the ratio of the pure modulus of elasticity (MOE) to the modulus of rigidity (*G*). Later work by Skaggs and Bender (1995) reiterated this concept: "Shear deflection for wood beams can exceed the bending deflection in certain situations due to the relatively low shear modulus of wood, and it should be considered."

Skaggs and Bender (1995) noted, "Common engineering practice for calculating deflection of wood beams is to use only flexural equations derived for bending only, and since the design *E* is reduced to account for shear deflection, they give reasonably accurate predictions for span-to-depth (*L*/*d*) ratios ranging from 15 to 25. However, if the *L*/*d* ratio is

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less than 15, the predicted deflection will be significantly less than the actual deflection. Simple methods of predicting shear stress and deflection are needed for layered composite wood beams" (Skaggs and Bender 1995). This L/d ratio range of 15 to 25 is for wood and ultimately relates to the ratio of a given wood's MOE for bending as compared with its shear stiffness and it can change for engineered composite beams. For example, in the case of cross-laminated timber (CLT) evaluation, span-to-depth ratios on the order of 28 to 30 (ANSI/APA PRG-320 2018, Spinelli Correa 2022, Spinelli Correa et al., in press) are recommended to avoid shear failure during mechanical testing. This action occurs because the shear stiffness of wood across the grain (rolling shear), as occurs in CLT panels stressed in bending, is less than the shear stiffness of wood along the grain. Thus, the span-to-depth ratio must be increased to encourage bending rather than shear failure. The modulus of rigidity (G) parallel to the grain is approximately 1/16 of MOE (Forest Products Laboratory 2021, table 5-1). The shear stiffness of wood across the grain, wherein rolling shear can develop, is less. With reference to rolling shear in CLT, Karacabeyli and Douglas (2013) state "in the product standard, the rolling shear modulus G_R is assumed to be 1/10 of the shear modulus parallel to the grain of the laminations, G_0 (i.e., $G_R \sim G_0/10$)."

Generally, shear deflection is often negligible in the case of elongated wood beams with span-to-depth ratios of approximately 18:1 or greater. Routinely it is considered as contributing 5 percent or less of overall deflection. In the case of wood composites, however, shear deflection can be important, particularly when material of lesser modulus of rigidity is located at or near the neutral axis. Additionally, as a beam's span-to-depth ratio decreases, the role of shear stress and deflection become more prominent.

Structural insulated panels

In structural insulated panels (SIPs), the foam core is subjected to shear stress. The foam core's relatively deep section and location at the neutral axis render its shear performance, particularly its influence on shear deflection, of importance. Information regarding the modulus of rigidity for foam varies. Vejelis et al. (2008) investigated the G value of expanded polystyrene (EPS) for material in the 0.69 to 1.87 lb/ft^3 density range. Therein, foam G values varied with foam type, test method, and specimen thickness. Shear modulus values in the range of approximately 130 to 640 psi were reported across a range of test conditions. Yoshihara and Maruta (2019) also reported on the G value of foam. They investigated extruded polystyrene foam (XPS) in the 1.62 to 2.25 lb/ft^3 density range. The G value varied by foam type/density as well as $x/y/z$ axis orientation. Shear moduli values ranged from 1,000 to 2,250 psi across their testing. The material of Yoshihara and Maruta was denser than that that is specified for use in SIPs and is XPS, not EPS, as was considered in this research. MatWeb (accessed March 2023) lists the shear modulus (G) for EPS as 280 to 640 psi. Finally, Table 1 of the ICC-ESR 4689 code report, which was the basis for manufacturing the SIPs in this study, shows a strong axis bending G of 405 psi for the EPS foam.

In this study, 6.5-in-deep and 12.25-in-deep SIP test specimens were investigated and the bending deflection due to shear deformation was computed. The shear modulus of the foam core was also determined on the basis of the shear deflection of the SIP specimens.

Materials and Methods

Test specimens

SIPs were manufactured at a Structural Insulated Panel Association (SIPA) member's commercial facility in accordance with International Code Council, Evaluation Service Report 4689. Two SIP depths, 6.5 and 12.25 in deep, were evaluated. All specimens were approximately 11.5 in wide. Because of being manufactured at two different times, approximately half of the matched specimen pairs in each depth class had a foam density of approximately 1.0 lb/ft^3 and approximately half of the matched specimen pairs in each depth class had a foam density of approximately 1.2 lb/ft3. Data from beams of differing foam densities were pooled because the SIPs were considered commodity products with nondiffering design properties. Thus, potential differences related to foam densities are not considered herein.

The SIPs had type I EPS foam cores with 7/16-in-thick oriented strand board (OSB) facers. The facers were APA—The Engineered Wood Association performance-rated panels (PR-N610; 2022). The strong axis of each facer was oriented parallel with the length of each SIP specimen.

Each specimen contained discontinuities (i.e., butt-jointed foam) located in the zone of maximum shear (one at either end between the reaction support and the load head). These butt joints were intended to simulate the butt joints in SIPs that can exist in normal production and use.

Specimens were matched into pairs with respect to parent panels. One element of the pair was subjected to static bending destructive testing. The other element of the pair was subjected to a 90-day full-scale creep test followed by static bending destructive testing. Of interest was the role of shear deflection of the SIP specimens both before and after creep testing. Specimens were tested using a universal testing machine built by Instron with a load capacity of 135 kips. Mid-span deflection at the neutral axis was measured using a string potentiometer with 25-in measuring range.

Testing

For the first set of specimens, destructive static testing was conducted in short-duration one-third-point bending per ASTM-D6815 (ASTM 2015). Both specimen depths, 6.5 and 12.25 in, were tested in this manner.

Figure 1 illustrates an exemplar of full-scale 12.25-in-deep SIP test specimen in the one-third-point bending test fixture at the start of the short-term bending test. Specimens were tested in one-third-point flexure at an approximate 18:1 span-to-depth ratio. Thus, spans for the 6.5- and 12.25-in-thick SIPs were 117 and 216 in, respectively. The rate of loading was adjusted to achieve a time to failure of approximately 1 minute in all cases, per the testing standard.

The second set of specimens was subjected to creep testing per ASTM-D6815 (2015). Figure 2 illustrates the specimens at the start of the creep test. Creep load levels were at the 5-percent point estimate for bending stress per ASTM-D6815 as developed from the data from the first set of test specimens. After the 90-day creep test followed by a 30-day unloaded cycle, the second set of specimens was unloaded, transported to the laboratory, and tested in static bending. The static bending protocol followed that of the first set of specimens. In all cases, failure originated in the foam at one of the butt-joint discontinuities (Fig. 3).

Table 1.—Shear modulus and shear deflection of the foam of 6.5-in-deep structural insulated panels (SIPs).

		664,000 psi MOE[a] for OSB			931,000 psi MOE for OSB		
	$\Delta y_{\text{max obverved}}$ (in)	$\Delta y_{\text{OSB flexure}}$ (in)	$\Delta y_{\text{foam shear}}$ (in)	G_{foam} (psi)	$\Delta y_{\text{OSB flexure}}$ (in)	$\Delta y_{\text{foam shear}}$ (in)	G_{foam} (psi)
Before creep testing ($n = 31$)							
Mean	1.27	0.51	0.76	546	0.36	0.91	450
Median	1.27	0.49	0.74	440	0.35	0.88	379
SD	0.11	0.06	0.14	150	0.04	0.13	104
COV (%)	8.95	11.9	18.4	27.5	11.9	14.4	23
Minimum	1.04	0.41	0.56	388	0.30	0.70	340
Maximum	1.51	0.63	1.01	779	0.45	1.15	606
After creep testing ($n = 29$)							
Mean	1.36	0.51	0.85	481	0.37	1	406
Median	1.37	0.50	0.85	412	0.35	0.99	358
SD	0.10	0.08	0.09	112	0.06	0.09	79.8
COV	7.23	16.1	10.75	23.3	16.1	8.59	19.6
Minimum	1.16	0.40	0.64	357	0.29	0.81	316
Maximum	1.54	0.63	1.04	738	0.45	1.17	581
P value for difference before versus after*	0.001	0.412	0.004	0.032	0.412	0.002	0.035

[a] MOE = modulus of elasticity; OSB = oriented strand board; COV = coefficient of variation.

* *P* value for difference before versus after creep testing: *t* test, one tail, equal variance. Assume OSB stiffness didn't change.

Determination of shear deflection

In the case of SIPs, shear deflection cannot be neglected because of the foam core with low shear modulus. In this case, the deflection was the sum of the bending deflection plus the shear-based deflection. As such, shear-based deflection was developed on the basis of the following equation:

$$\Delta y_{\text{max observed}} = \Delta y_{\text{flexure}} + \Delta y_{\text{shear}} \tag{1}$$

where $\Delta y_{\text{max observed}}$, $\Delta y_{\text{flexure}}$, and Δy_{shear} are deflection at mid-span at maximum load (P_{max}), deflection due to bending stiffness of the SIP, and deflection due to shear deformation of the SIP, respectively. In the case of one-third-point flexure of square section beams, the pure bending deflection is (AWC 2007):

$$\Delta y_{\text{flexure}} = \frac{P_{\text{max}} a}{48EI}\left(3L^2 - 4a^2\right) \tag{2}$$

where P_{max}, a, E, I, and L are maximum bending load, the distance between the support and loading point, which is $L/3$ in this study, MOE of the SIP, moment of inertia of the SIP about its neutral axis, and span length, respectively. In the case of laminated structures such as SIPs, effective bending stiffness based on the shear analogy theory, $EI_{\text{eff, shear}}$, should be computed using Equation 3 and substituted in Equation 2 to determine the flexural deflection (He et al. 2018):

$$EI_{\text{eff, shear}} = \sum_{k=1}^{n} E_k I_k + \sum_{k=1}^{n} E_k A_k Z_k^2 \tag{3}$$

where E_k, I_k, and A_k are MOE, moment of inertia, and cross-section of each layer. Z_k is the distance from the centroid of the kth layer to the centroid of the SIP's cross-section.

The stiffness of OSB is well studied and is routinely on the order of 600,000 to 1,000,000 psi with respect to bending along its strong axis (Forest Products Laboratory, 2021, table 12-3). At the commercial scale, the minimum MOE for 7/16-

Figure 1.—Full-scale 12.25-in-deep specimen in the one-third-point testing fixture. Note string deflection gauge affixed at the neutral axis at mid-span to capture maximum deflection.

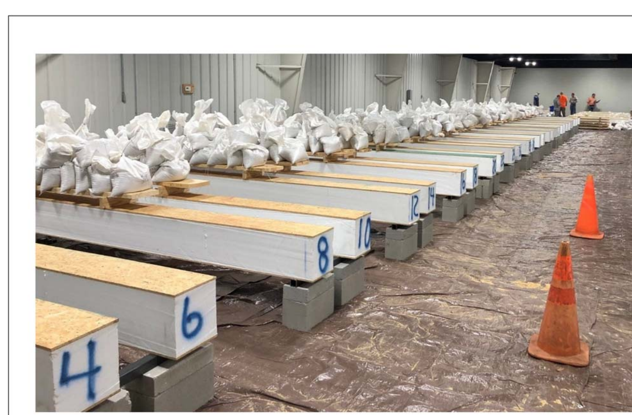

Figure 2.—Structural insulated panel specimens being loaded at initiation of 3-mo creep test. All specimens were loaded in one-third-point bending.

Figure 3.—Failure in 6.5-in-deep structural insulated panel. Failure initiated at a butt-jointed foam discontinuity in all specimens.

in-thick OSB for SIP facers is 664,000 psi, as derived from APA Product Report PR-N610 (2022), which lists a flatwise stiffness (*EI* product) as 55,600 lbf-in^2/ft for a 12-in-wide section. Arithmetically, 55,600 lbf-in^2/ft per 0.0837 in^4 (the moment of inertia of a 7/16-in-thick by 12-in-wide section) equals 664,000 psi. Because this is a minimum quality-assurance property based on small-scale bending test specimens, one can anticipate that the stiffness of OSB facers is typically higher. For example, table 9 of the APA Panel Design Specification (2020) lists an *EI* value of 78,000 for 7/16-in 24/16-rated OSB. This equates to an *E* value of 931,450 psi, which is commonly used by design professionals in assessing OSB-based designs. The MOE of EPS foam, however, is negligible compared with that of OSB as EPS foam with density of 1.2 lb/ft^3 showed an average MOE of 1,435 psi (Gnip et al. 2007). Therefore, the bending stiffness of the foam core in Equation 2 should be neglected, and only that of OSB should be used to compute the effective bending stiffness of the SIP. In other words, OSB facers will dominate the flexural deflection of the SIPs and contribution of foam core is negligible.

Therefore, P_{max}, fixed MOE value of 664,000 psi (per APA Product Report PR-N610 2022) or 931,000 psi (per APA Panel Design Specification 2020) for the OSB, and moment of inertia of the OSB about their position with respect to the neutral axis of the SIP were used in Equation 2 to determine flexural deflection of the SIP ($\Delta y_{\text{flexure}}$) due to bending stiffness. The OSB MOE value of 664,000 psi is the minimum acceptable value for the SIP products. An additional assumption maintained herein was that the MOE value for the OSB did not change during the creep testing.

After computing the flexural deflection of the SIP using Equation 2, the shear deflection of the SIP can be determined using Equation 1.

Determination of shear modulus

Shear-based deflection was based on the premise that in addition to the elongation and compression of fibers from bending, there is further deflection due to shear stresses (Newlin and Trayer 1956). Both flexural and shear deflections of the SIP were determined in the previous section and the relation between flexural deflection and bending stiffness (*EI*) was given in Equation 2. The relation between shear deflection and shear stiffness ($GA = Gbh$) is (Newlin and Trayer, 1956):

$$\Delta y_{\text{shear}} = \frac{0.2P_{\max}L}{bhG} \tag{4}$$

where *b*, *h*, and *G* are specimen width, specimen depth, and modulus of rigidity (shear modulus) of the SIP, respectively. In the case of SIPs as a laminated structure, effective shear stiffness, $(GA)_{\text{eff}}$, should be computed using Equation 5 and substituted in Equation 4 to determine the shear deflection (He et al. 2018).

$$GA_{\text{eff}} = \sum_{k=1}^{n} G_k b_k h_k \tag{5}$$

where G_k, b_k, and h_k are shear modulus, width, and depth of each layer, respectively. As discussed in the Introduction, shear modulus values in the range of 130 to 2,250 psi have been reported by other researchers for EPS foam. However, a sheer modulus of 343,500 psi has been reported for OSB (Plenzler et al. 2013). Considering the high shear modulus of the OSB compared with that of the foam core, the shear deformation of the SIP will be controlled by the foam core. In addition, the OSB facers are mainly subjected to normal stresses, axial tension, and compression. Given their relatively thin section (7/16 in) compared with the overall SIP depth (ranging from approximately 4.5 to 12.25 in), the shear stress developed in the OSB facers is small. Therefore, the effective shear stiffness of the SIP given in Equation 5 will be computed using the shear modulus, width, and depth of the foam, and the small contribution of the OSB facers will be neglected. Considering this, Equation 4 can be rewritten to find the shear modulus of the foam using the shear deflection of the SIP obtained in the previous section. This is rearranged to compute shear modulus:

$$G_{\text{foam}} = \frac{0.2P_{\max}L}{bh_{\text{foam}}(\Delta y_{\text{shear}})} \tag{6}$$

As explained, flexural deflection of the SIP mainly due to high MOE of OSB, known as $\Delta y_{\text{OSB flexure}}$, shear deflection of the SIP mainly due to low shear modulus of foam core, known as $\Delta y_{\text{foam shear}}$, and shear modulus of the foam, known as G_{foam}, were calculated using Equations 2, 1, and 6, respectively. Summary statistics of these properties for the 6.5- and 12.25-in-deep specimens are shown in Tables 1 and 2, respectively.

It should be highlighted that although Equations 2 and 4 are valid for the elastic region, these relations have been used for maximum load (P_{max}) to compute maximum shear and flexural deflections as load-deflection curves of the SIP specimens were almost linear. The load-deflection curves for several SIP specimens with 6.5- and 12.25-in-thick foam core are given in Fig. 4.

Results and Discussion

This work investigated the factor *G* (shear modulus) of SIP specimens both before and after creep testing. Related work by the authors demonstrates that full-scale creep test

Table 2.—Shear modulus and shear deflection of the foam of 12.25-in-deep structural insulated panels (SIPs).

		664,000 psi MOE[a] for OSB			931,000 psi MOE for OSB		
	$\Delta y_{\text{max observed}}$ (in)	$\Delta y_{\text{OSB flexure}}$ (in.)	$\Delta y_{\text{foam shear}}$ (in.)	G_{foam} (psi)	$\Delta y_{\text{OSB flexure}}$ (in.)	$\Delta y_{\text{foam shear}}$ (in.)	G_{foam} (psi)
Before creep testing ($n = 32$)							
Mean	1.66	0.92	0.73	544	0.66	1	398
Median	1.67	0.93	0.74	530	0.66	1	392
SD	0.12	0.09	0.07	68.3	0.06	0.08	36.2
COV (%)	7.12	9.45	9.32	12.6	9.45	7.61	9.09
Minimum	1.46	0.77	0.59	460	0.55	0.85	352
Maximum	1.85	1.08	0.89	676	0.77	1.16	466
After creep testing ($n = 30$)							
Mean	1.69	0.9	0.79	498	0.64	1.05	372
Median	1.75	0.9	0.81	488	0.64	1.08	368
SD	0.22	0.13	0.13	101	0.09	0.15	50.6
COV	13.1	13.9	16.0	20.3	13.9	14.2	13.6
Minimum	1.18	0.61	0.37	375	0.43	0.60	300
Maximum	2.21	1.09	1.15	945	0.77	1.45	580
P value for difference before versus after	0.205	0.209	0.012	0.019	0.209	0.041	0.01

[a] MOE = modulus of elasticity; OSB = oriented strand board; COV = coefficient of variation.

* *P* value for difference before versus after creep testing: *t* test, one tail, equal variance. Assume OSB stiffness didn't change.

loading does not affect P_{max} or Δy_{max}. In this research, shear deformation in the foam was a significant contributor to observed deflection. The results show that the shear deflection reported in Tables 1 and 2 ranged from 44 to 73 percent of the total deflection observed depending on specimen depth and the assumed MOE of the OSB facers. Average *G* values for the foam in both SIP depths were similar in magnitude and ranged from 372 to 546 psi depending on before versus after creep testing, specimen depth, and assumed MOE of the OSB. These *G* values for the EPS foam herein are in the range of those reported by others for EPS foam of comparable density.

Changes in G_{foam} for each of the cases cited above was considered to be statistically different before and after creep testing. However, the effect of these differences on the foam contribution to the shear deflection as a percentage of the overall deflection was within ±3 percent in all cases. This indicates a relatively minimal impact of the foam density differences in determining the shear deflection of SIPs before and after creep testing.

Conclusions

For the 6.5-in-deep specimens with OSB MOE at the 664,000-psi level, the overall observed deflection is greater after versus before creep testing. This difference is statistically significant ($P = 0.0009$). However, the difference is relatively small in magnitude, i.e., 1.27 versus 1.36 inches. Across the 117-in span, this 0.09-in difference equates to an *L*/1,300 value that would be considered to be of minimal impact in a design situation. This difference appears to be mainly due to shear deflection attributed to the foam. The *P* values for deflection differences due to OSB and foam were 0.412 and 0.00359, respectively. The average G_{foam} changed from 546 to 481 psi before versus after creep testing. This change was statistically significant ($P = 0.0317$). When parsed out, the shear deflection from the foam contributed to 60 and 62 percent of the overall observed deflection before versus after creep testing, respectively.

For these 6.5-in-deep specimens with OSB MOE at the 931,000-psi level, the overall observed deflection is the same as the previous analysis. The *P* value for deflection differences due to OSB and foam were 0.412 and 0.0018, respectively. The average G_{foam} changed from 450 to 406 psi before versus after creep testing. This change was statistically significant ($P = 0.0351$). When parsed out, the shear deflection from the foam contributed to 71 and 73 percent of the overall observed deflection before versus after creep testing, respectively.

For the 12.25-in-deep specimens with OSB MOE at the 664,000-psi level, overall observed deflection is not significantly

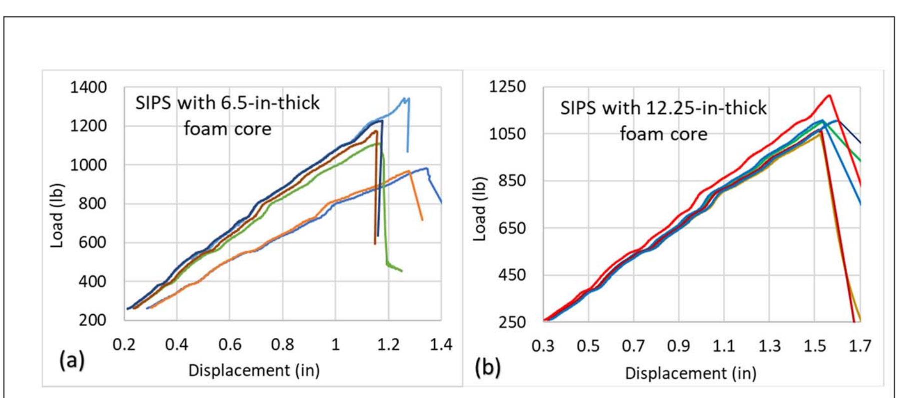

Figure 4.—Linear load-deflection curves for structural insulated panel (SIP) specimens with (a) 6.5-in- and (b) 12.25-in-thick foam core.

different before versus after creep testing ($P = 0.205$). The P values for deflection differences due to OSB and foam were 0.209 and 0.0123, respectively. The average G_{foam} changed from 544 to 498 psi before versus after creep testing. This change was statistically significant ($P = 0.0189$). On average, the shear deflection from the foam contributed to 44 and 47 percent of the overall observed deflection before versus after creep testing, respectively.

For these 12.25-in-deep specimens with OSB MOE at the 931,000-psi level, the overall average observed deflection is the same as the previous analysis. The P value for deflection differences due to OSB and foam were 0.209 and 0.0409, respectively. The average G_{foam} changed from 398 to 372 psi before versus after creep testing. This change was statistically significant ($P = 0.00963$). When parsed out, the shear deflection from the foam contributed to 60 and 62 percent of the overall observed deflection before versus after creep testing, respectively.

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