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ULTIMATE FLEXURAL STRENGTH AND LONG-TERM CREEP DEFLECTION FOR STRUCTURAL INSULATED FOAM-TIMBER SANDWICH PANELS

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ABSTRACT

The structural insulated panel (SIP) is a sandwich structured composite that is prefabricated by attaching a lightweight thick core made of Expanded Polystyrene (EPS) foam laminated between two thin, and stiff face skins made of Oriented Strand Board (OSB). The use of sandwich panels provides key benefits over conventional materials including: very low weight; high stiffness; durability and; production and construction cost savings. The facing skins of the sandwich panel can be considered as the flanges for the I-beam carrying bending stresses in which one face skin is subjected to tension, and the other is in compression. The core resists the shear loads and stabilizes the skin faces together giving uniformly stiffened panel. OSB is wood product that shrinks when dry and swells when adsorb moisture either due to liquid or vapor from the surrounding atmosphere. The relative combination of relative humidity and temperature is introduced into the equilibrium moisture content (EMC) that increases with the increase of the relative humidity and with decreasing temperature. Experimental test matrix includes testing 2.44 m (8') and 4.88 m (16') long SIPs for 5 years under different sustained loads and weather resistive barriers (WRBs), recording creep deflection, relative humidity and temperature. After creep recovery, the SIPs are loaded to-collapse to determine their flexural strength.

Keywords: Structural Insulated Panel (SIP), Creep Deflection, Flexural Strength, OSB-Wood, EPS-Foam.

1. INTRODUCTION

The concept of the structural insulated panels (SIPs) begun in 1935 at the Forest Products Laboratory (FPL) in Madison, Wisconsin. SIPs were constructed using structural sheathing and insulation. The architect Frank Lloyd Wright built Usonian house in 1930's. Wright's student Alden B. Dow created the first foam-cored SIP in 1952. Today SIPs offer high tech solution for residential and low rise non-residential buildings. SIPs are made with variable structural skin materials including oriented strand board (OSB), treated plywood, fiber-cement board, metal and fiber reinforced polymers (FRP) sheets. SIPs thickness vary from 100 mm (4 inch) and 152 mm (6 inch) walls and thicker for the roof panels up to 355 mm (14 inch). The OSB skinned system with EPS foam core can be used for the floor, wall, and roof. SIPs share the same structural properties as the I-beam or I-column. The rigid insulation foam-core acts as the web, while the OSB sheathing acts as the flanges. The mechanical behavior of the sandwich panel, and SIP failure modes includes: (i) failure of the skin face (yielding or fracture); (ii) wrinkling and dimpling of the face; (iii) shear failure of the core materials; (iv) shear crimping of the core material (instability phenomenon); (v) overall buckling (and interaction effects with local failure modes); (vi) delamination of the interface between the core and the face; (vii) long-term creep; and (viii) overall and local deflections. Thus, detailed calculation should cover the stiffness, deflection, including shear deflection, facing skin stress, core shear stress, panel buckling if applicable, shear crimping, skin wrinkling, intracellular buckling, local compression loads on core, and face/core interface stress.

The deflection of straight beam that are elastically stressed have a constant cross-section throughout their length is given by Equations 1 to 5. Where Δ_{ID} is the instantaneous deflection, P is total beam load acting perpendicular to beam neutral axis, L is beam span, k_b and k_s are constants dependent upon beam loading, support conditions, and location of point whose deflection is to be calculated, I_f is face-skin moment of inertia, E_f is face-skin modulus of elasticity, D is the flexural rigidity, $G = G_c$ is beam shear modulus of the core, t_f is the thickness of the face-skin, t_c is the thickness of the core, b is the width of the panel and S is the shear rigidity. The values of k_b and k_s equal to 5/384 and 1/8, respectively, for the uniformly distributed load for simply-supported beam, and recorded deflection at the mid-span. The values of k_b and k_s equal to 11/768 and 1/8, respectively, for the concentrated loads at outer quarter span points over simply-supported beam, and recorded deflection at the mid-span (Rammer, 2010).

[1] $D = E_f I_f = \frac{E_f t_f h^2 b}{2}$

[2] $S = bhG_c$ where $h = t_f + t_c$ and $G_c = \frac{E_c}{2\,(1+\upsilon)}$

[3] $\Delta_{ID} = \Delta_{Bending} + \Delta_{Shear} = \frac{k_b\,PL^3}{D} + \frac{k_s PL}{S}$

The bending moment and shear force can be determined from Equations 6 and 7

[4] $M = \frac{PL^2}{8}$ and $V = \frac{PL}{2}$ under uniform distributed load (UDL)

[5] $M = PL/4$ and $V = P$ under concentrated two-points load at quarter the span

Facing Stress: [6] $\sigma_f = \frac{M}{h\,t_f b}$

Core stress: [7] $\tau_c = \frac{V}{hb}$

Creep is time-dependent deformation subjected to constant load over time, under steady relative humidity and temperature. The initial (instantaneous) deflection due to applied occurs at the start of creep, and it obeys the basic model of Hooke's law ($\sigma = E\epsilon$). The fractional creep K_{creep} is the ratio of maximum deflection at end of creept test to instantaneous deflection. In wood, creep includes three distinct type of behavior, which is difficult to separate because they can all operate simultaneously. These are time-dependent (viscoelastic) creep, mechano-sorptive (moisture-change) creep, and the pseudo-creep and recovery that have been ascribed to differential swelling and shrinkage (Hunt, 1999). Creep-strain response for wood structure is viscoelastic, represented by elastic spring and viscous dashpot. Viscous flow to ideal fluid requires rate of strain with respect to time be proportional to the applied stress, obeying Newton's law ($\sigma \propto d\epsilon/dt = \eta\ d\epsilon/dt$), while plastic deformation is due to irreversible changes of position, where strain doesn't change when stress is removed ($\epsilon = \sigma t/\eta$) (Sayed-Ahmed & Sennah, 2013).

[8] $K_{creep} = \Delta_{MD}/\Delta_{ID}$ and [9] $\Delta_{Total} = K_{creep}\Delta_{ID}$

The dependence of equilibrium moisture content (EMC) on the relative humidity and temperature between (-1.1˚C and 65.5˚C) can be calculated with the following equations (Simpson, 1973) and (Forest Products Laboratory, 1987), where T is temperature h is relative humidity (%/100), EMC is moisture content (%) and W, K, K_1, K_2 are coefficients of an adsorption model developed by (Hailwood & Horrobin, 1946).

[10] $EMC = \frac{1800}{W}\frac{Kh}{1-Kh} + \frac{K_1Kh + 2\,K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2}$

For temperature in Celsius,

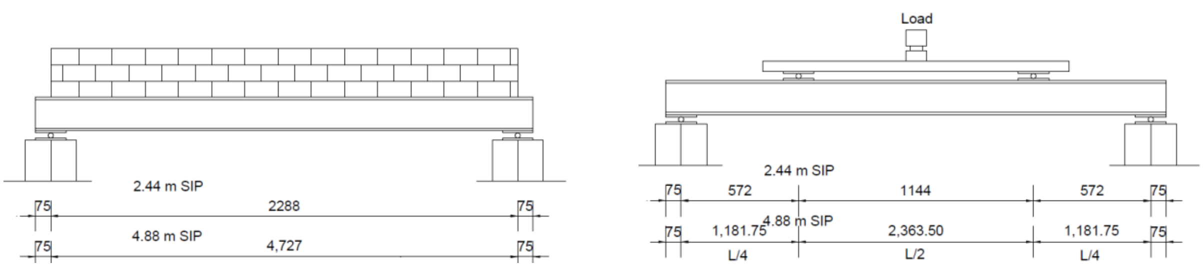
[11] $W = 349 + 1.29\,T + 0.0135T^2$ and [12] $K = 0.805 + 0.000736T - 0.00000273T^2$

[13] $K_1 = 6.27 - 0.00938T - 0.000303T^2$ and [14] $K_2 = 1.91 + 0.0407T - 0.000293T^2$

This experiment investigates the short-term and long-term creep deflection for the structural insulated panels under constant loading for a period of 5 years. Some SIPs were wrapped by plastic sheets to simulate the weather resistive barrier (WRB) and isolate the SIP from the external weather, especially the vapour content. Short-term deflection is the instantaneous deflection that equals to the deflection due to bending and shear. The five-year long-term deflection was recorded with the associated relative humidity and temperature. After creep recovery, SIPs were subjected to ultimate load to-collapse to determine their flexural strength. This research program aims at developing a better understanding of the structural behavior of SIPs at service and ultimate loading conditions when they act as floors and ceilings in the residential construction.

2. EXPERIMENTAL PROGRAM

SIPs (Thermapan Structural Insulated Panels, 2009) are composed of thick layer of Expanded Polystyrene (EPS) foam board laminated between two sheets of Oriented Strand Board (OSB). Tested SIPs included two geometric characteristics, namely: (i) panel size 2438x305x165 mm (8'x1'x6½") and (ii) panel size 4877x305x260 mm (16'x1'x10¼"). The material of the 11 mm (7/16") thick OSB construction sheathing was of 1R24/2F16/W24 panel mark with the following specifications: bending resistance 228 N.mm/mm, bending stiffness 730,000 N.mm^2/mm, axial stiffness 38,000 N/mm, axial tensile resistance 57 N/mm, axial compression resistance 67 N/mm, shear through thickness resistance 44 N/mm and shear through thickness rigidity 11,000 N/mm. The EPS foam-core type 1 has been used and it has the following specifications: nominal density of 16 kg/m^3, flexural strength 172 kPa, tensile strength 103 kPa, compressive strength 70 kPa, shear strength of 83 kPa and shear modulus 2758 kPa. The off-white one-part polyurethane structural adhesive used to connect the foam to the facings (Sayed-Ahmed, 2011).



a. Creep test with uniformly distributed loading b. Two-point loading flexural test

Figure 1: Typical creep and flexural test setup (ASTM Subcommittee E06.11, 2015)

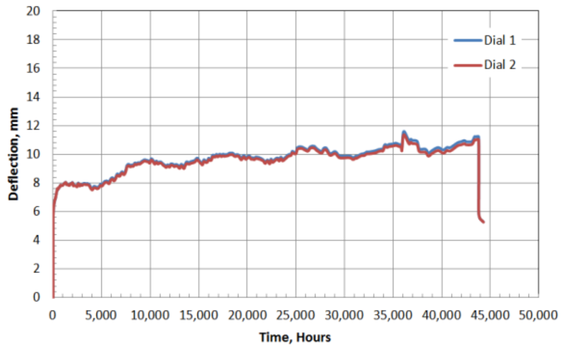
The test matrix shown in Table 1 included 2.44-m and 4.88-m long panels named C1 to C8. Each identical bare of SIP passed the same load level, either exposed to the weathering condition or covered with plastic sheets simulating the WRB condition. Figure 1 depicts the test setup for the creep test and the flexural test. Each panel was supported over two steel rollers of 25.4 mm diameter and 300 mm long, with 300x150x12 mm steel plate between each supporting roller and the specimen. Solid concrete bricks of 6.44 lbs and 200x100x60 mm dimensions were used to apply the UDL over the SIP specimens. Analogue dial indicator were placed at the maximum bending moment location for the creep test, while potentiometers (POTs) connected to the data acquisition were used for the ultimate flexural test, all to measure deflection at the mid-span.

3. TEST RESULTS

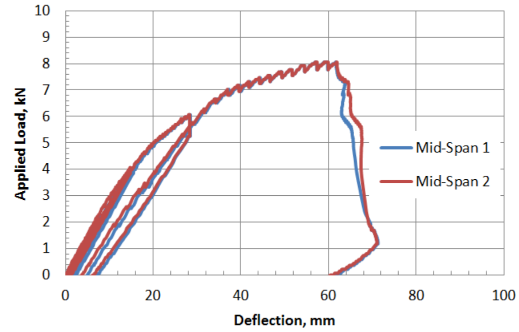
The National Building Code of Canada (NBCC, 2010) specified the applied loads on structures based on intended occupancy with live load for residential construction taken as 1.9 kPa, and 2.4 kPa for the work areas within live or work units, respectively. In this research, deal load over floor is assumed 0.5 kPa. Based on wood design in Canada (CSA, 2009), the following deflection criteria may be considered.

[15.1] $\Delta_L \leq L/360$ for live load over floor
[15.2] $\Delta_L \leq L/240$ for live load over roof
[15.3] $\Delta_T \leq L/180$ for total dead and live load

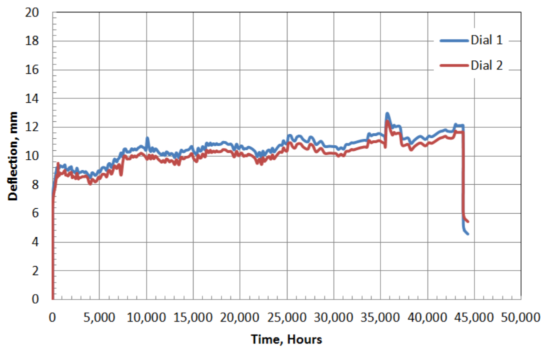
It should be noted that the total sustained uniform load considered in the creep test was 3 kPa, including 0.5 kPa dead load and 2.5 kPa live load. Figures 2 and 3 depict the instantaneous and creep deflection-time relationships of the 2.44-m and 4.88-m long panels up to 5 years (43,800 hours), along with the load-deflection curves resulting from loading each panel in flexure to-failure after conducting the creep tests. Table 1 summarizes the resulting deflection values at different stages of creep load history and creep recovery as well as the ultimate load and corresponding deflection at failure resulting from the static load test conducted after the creep test.



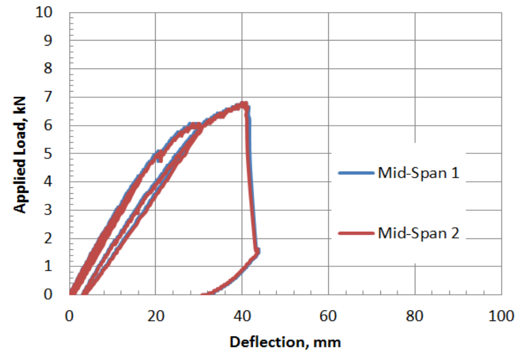
a. Creep deflection-time relationship for C1



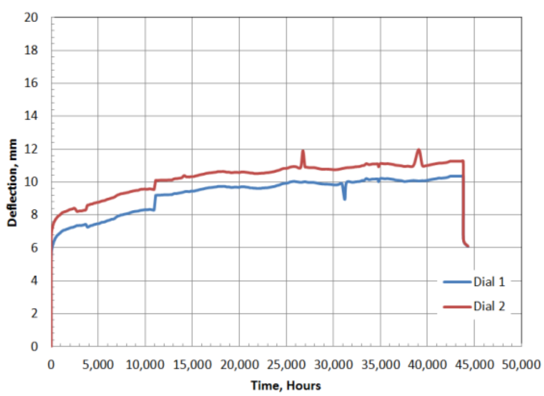
b. Flexural load-deflection curves for C1



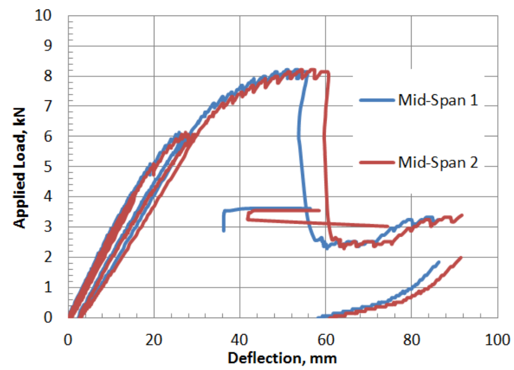
c. Creep deflection-time relationship for C2



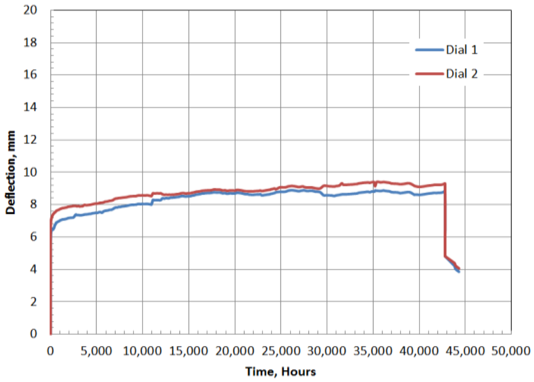
d. Flexural load-deflection curves for C2

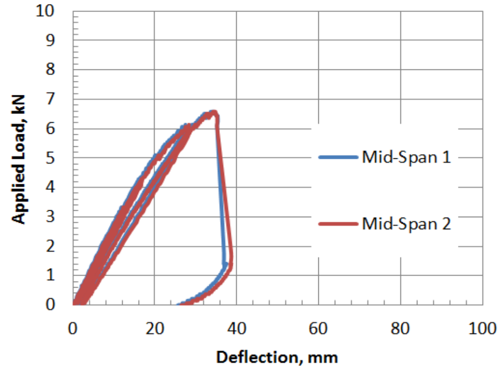


e. Creep deflection- time relationship for C3



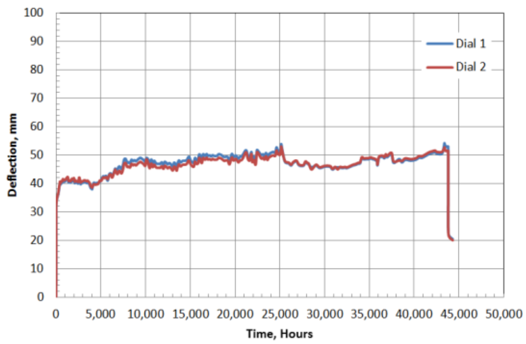
f. Flexural load-deflection curves for C3

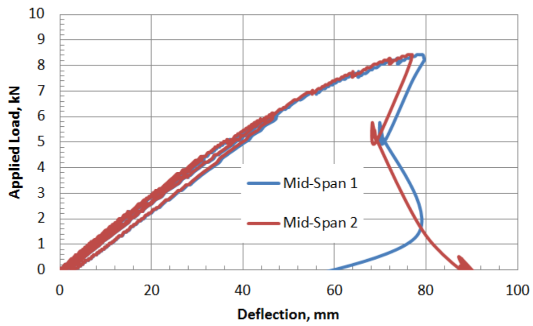




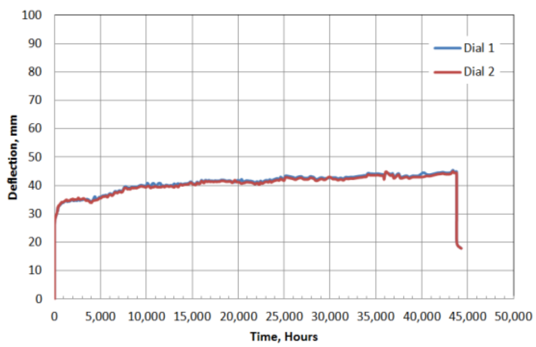
g. Creep deflection-time relationship for C4 h. Flexural load-deflection curves for C4

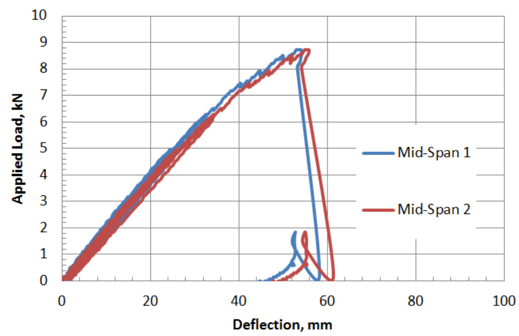
Figures 2: Creep deflection and ultimate flexural loading for the 2.44-m long SIPs C1 to C4



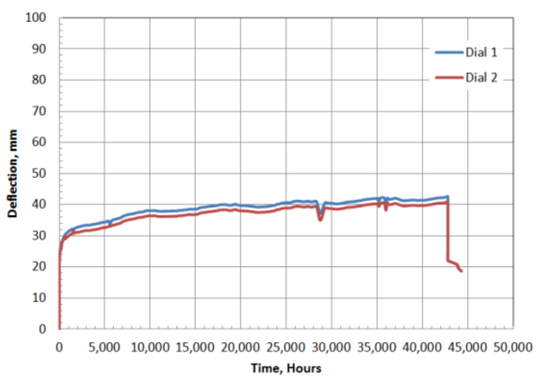


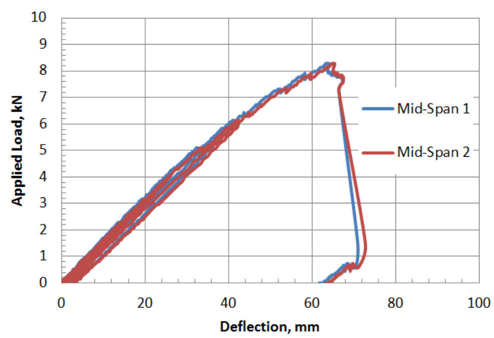
a. Creep deflection-time relationship for C5 b. Flexural load-deflection curves for C5



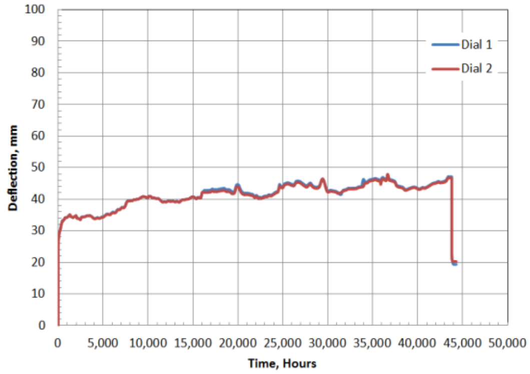


c. Creep deflection-time relationship for C6 d. Flexural load-deflection curves for C6

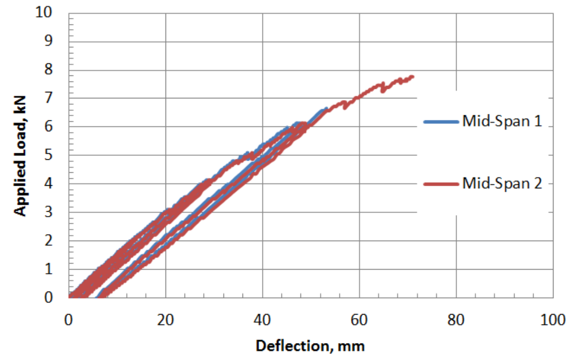




e. Creep deflection-time relationship for C7 f. Flexural load-deflection curves for C7



g. Creep deflection-time relationship for C8



h. Flexural load-deflection curves for C8

Figure 3: Creep deflection and ultimate flexural loading for the 4.88-m long SIPs C5 to C8

Table 1 shows that the instantaneous deflection of the 2.44-m long panels C1 and C2 are 5.52 and 6.93 mm, with an average value of 6.23 mm. This average total deflection is less the deflection limit of span/180 for total load (i.e. 13.55 mm). Specimens C3 and C4 are identical to C1 and C2 except that they were encased with plastic sheet to isolate them from the environment. It can be observed that the average instantaneous deflection for these two panels is 6.45 mm. Also, Table 1 shows that the instantaneous deflection of the 4.88-m long panels C5 and C6 are 31.88 and 26.03 mm, with an average value of 28.96 mm. This average total deflection is slightly more than the deflection limit of span/180 for total load (i.e. 27.11 mm) by 6.8%. Specimens C7 and C8 are identical to C5 and C6 except that they were encased with plastic sheet to isolate them from the environment. It can be observed that the average instantaneous deflection for these two panels is 22.21 mm. This deflection value is less than the deflection limit for total load by 18%.

Table 1: Creep deflection and ultimate flexural loading for SIPs*

SIP No.	Status	Creep Deflection D + L KPa	Creep Deflection ID mm	Creep Deflection MD mm	fractional Creep	Creep Recovery IRD mm	Creep Recovery PD mm	Ultimate flexural Load, kN	Ultimate deflection mm	Failure Mode
C1	8’	0.5+2.5	5.52	11.58	2.10	6.16	5.26	8.06	59.05	Skin crushing
C2	8’	0.5+2.5	6.93	12.96	1.87	6.23	5.43	6.81	39.99	Skin crushing
C3	WRB8’	0.5+2.5	6.37	11.98	1.88	6.80	6.08	8.21	50.83	Skin crushing
C4	WRB8’	0.5+2.5	6.53	9.40	1.44	4.82	3.86	6.58	34.19	Skin crushing
C5	16’	0.5+2.5	31.88	54.21	1.70	24.49	19.99	8.43	78.01	Skin crushing, interface shear
C6	16’	0.5+2.5	26.03	45.40	1.74	20.99	17.85	8.73	54.87	Skin crushing
C7	WRB16’	0.5+2.5	19.99	42.59	2.13	21.98	18.59	8.29	64.76	Skin crushing
C8	WRB16’	0.5+2.5	24.42	47.84	1.96	22.66	19.36	8.29	73.65	Skin crushing, Interface shear

* D = dead load; L = live load; ID = instantaneous deflection, MD = maximum deflection after 5 years of creep testing, IRD = instantaneous recovery deflection, PD = permanent deflection.

Table 1 presents the panel’s maximum deflection after creep test. It can be observed that the fractional creep, taken as the ratio between the total deflection after creep test and the instantaneous deflection after 5 years of sustained loading, is an average of 2.00 for the 2.44- m long panels C1 and C2 exposed to the environment while it is 1.57 for panels but wrapped with plastic sheet to isolate them from the environment. On the other hand, the fractional creep after 5 years of sustained loading, is an average of 1.72 for the 4.88-m long panels C5 and C6 exposed to the environment while it is 2.05 for panels but wrapped with plastic sheet to isolate them from the environment. Given the contradiction in the findings for the 2.44-m and the 4.88-m long panels with respect to the effect of WRB, a conclusion cannot be reached. However, it is evident that the instantaneous deflection increased by an average of 1.85 after 5 years of sustained uniform loading. It should be noted that the instantaneous deflection should be increased in design due to creep effect over the service life of the structures which can be 75 years of services or as specified in design codes. Thus, this research can be extended to develop creep prediction model to estimate the creep fraction constant based on the expected number of years the structures will be in service.

Table 1 shows summary of the creep recovery and permanent deflection after releasing the creep loading off the tested panels. It can be observed that the average permanent deflections are 7.42 mm (span/329 as a ratio) and 18.95 mm (span/257 as a ratio) for the 2.44- and 4.88-m long panels, respectively. Results show that the effect of isolating the panel from the environment in permanent deflection after the creep test is insignificant. Table 1 presents the results from the static load test to-collapse in the form of failure load and maximum deflection at failure. The failure mode of these panels were due to skin crushing in compression at or near the mid-span point. However, in panels C5 and C8, such failure mode was accompanied by horizontal shear failure at the interface of the OSB sheet and the foam core. The ultimate failure load can be used further to qualify the panel for design at the ultimate limit state. However, static load test as well as creep test results are limited to two identical specimens in each panel group. Therefore, this research can be repeated with 5 identical specimen to have better representation of, and confidence in, the results.

4. CONCLUSIONS

Experimental results from the creep-deflection tests provide experimental data for creep deflection over five years of sustained loading. Creep tested results can be utilized to develop creep deflection prediction model for estimation of long-term deflection after 75 years of service or as required by the designer or design code. The fractional creep values reached in this research are limited to the size of the studies panels and for 5 years only. Also, results are limited to two identical specimens in each panel group. Therefore, this research can be repeated with 5 identical specimen to have better representation of, and confidence in, the results.

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