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Effect of Temperature and Relative Humidity on Creep Deflection for Permanent Wood Foundation Panels

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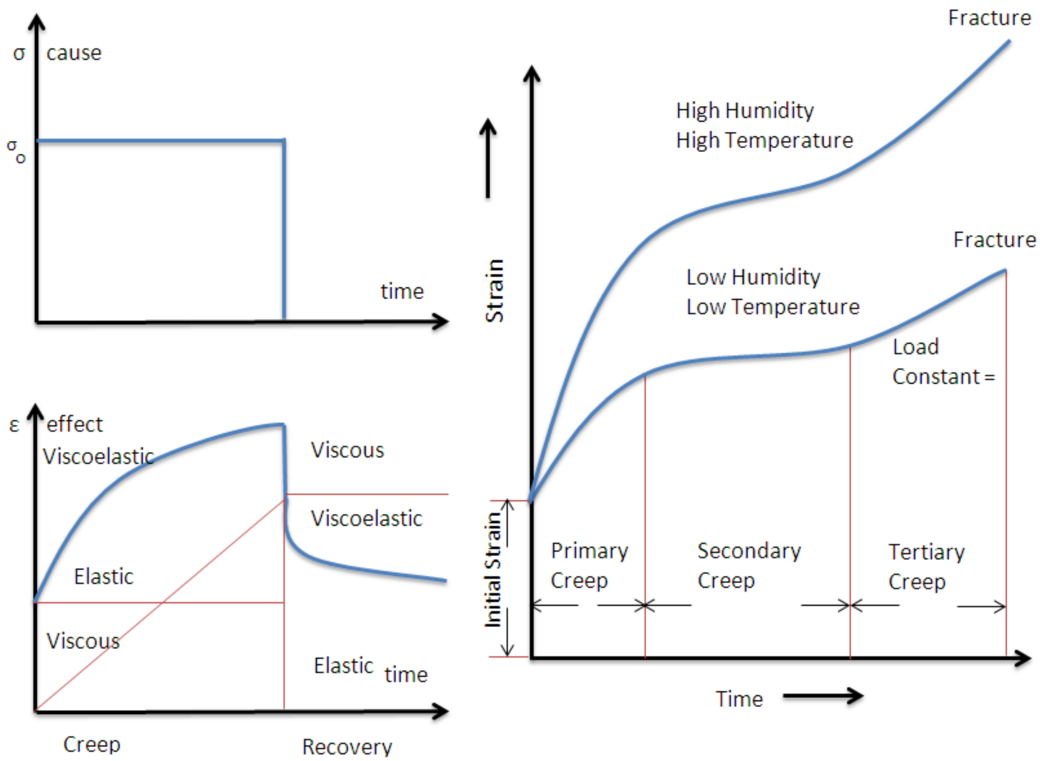
Abstract: The structural insulated panel (SIP) is an engineered composite product composed of an insulating foam core sandwiched to provide the insulation and rigidity, and two face-skin materials to provide durability and strength. SIPs can also be used as permanent wood foundation (PWF) for basements in low-rise residential construction to save in the energy cost. The maximum deflection equation specified in the Canadian Standard for Engineering Design of Wood, CAN/CSA-O86.09 specifies expressions for the effects of short-term bending deflection on the PWF timber stud walls. Information on the long-term creep behavior of SIPs under sustained triangular loading, simulating soil pressure, including effect of the change in ambient temperature and relative humidity is as yet unavailable. The long-term creep deflection for permanent wood foundation panels that is characterized as viscoelastic materials is highly affected by the change in ambient temperature and relative humidity. This paper reported the results from flexural creep experiments performed on two sets of different sizes of PWF made of structural-insulated foam-timber panels. In these tests, deflection, temperature and relative humidity were tracked for an eight-month period. The experimental findings were examined against existing creep models in the literature. Then, a creep model incorporating the effects of temperature and relative humidity on creep deflection was developed. Correlation between the proposed model and the experimental findings provides confidence on using the proposed model in the determination of the capacity of the PWF under combined gravity loading and sustained soil pressure as affected by temperature variation and relative humidity.

1 Introduction

Permanent Wood foundation (PWF) panel is a viscoelastic material at normal operating stress, temperature and relative humidity. PWF is susceptible to long-term creep deflection that accounts for time-dependent behavior of wood, and leads to serviceability and strength reduction. Long-term creep can be obtained by magnifying the short-term creep deflection. There is a lack of information about the long-term behavior and durability of the permanent wood foundation panel that used as primary structural applications for low-rise and residential buildings.

ASTM D6112 defines creep as the progressive deformation of a material at constant load (stress) applied to a specimen in selected loading configuration at constant temperature where the deformation is measured as a function of time (ASTM, 2010). The long-term mechanical behavior of viscoelastic materials can be represented by the common creep models for time-deflection which generate a smooth master curve by applying vertical shift along the time axis, while the principle of time-temperature superposition (TTSP) utilizes the horizontal shifting along the time axis. The material is classified as thermo-rheological simple materials (TSM), if it is represented by horizontal shift along the time axis, and is classified as thermo-rheological complex materials (TCM) if it is represented by vertical shift along the time axis. The Arrhenius activation energy equation can relate the rate of the deflection on the temperature for TCMs. The fractional deflection (FD) after ninety (90) days (minimum) for each surviving specimen shall not be greater than 2.00 to evaluate the acceptance of the wood-based products for long-term load behavior according to ASTM D6815-09 (ASTM, 2009). Wood is hygroscopic material that changes its dimensions to reach to the equilibrium moisture content (EMC) interacting with the surrounding environment from air temperature and relative humidity (Simpson, 1998; ASTM, 2010), where all changes in dimensions is across or perpendicular to the grain. Fig. 1 depicts schematic diagrams of creep-deflection over time and how it changes by the change of temperature and/or relative humidity.



(a) Creep and recovery: Stress, σ, and strain, ε, vs. time, t

(b) Regions of creep behaviour: Strain, ε, vs. time, t, for different Humidex

Fig.1: Schematic diagrams of viscoelasticity demonstration on creep

2 Experimental Program

The scope of the experimental study is (i) to develop common creep model parameters based on experimental findings, (ii) to propose creep-deflection model that considers the effect of temperature and relative humidity and (iii) to correlate the results from the proposed creep-deflection model with experimental findings. Two groups of specimens were considered in this study, representing a 1200-mm width strip of SIP foundation wall as shown in Fig. 2. The first group had three identical panels of 3.05-m length, 1.22-m width and 260-mm total depth, namely: BW1, BW2 and BW3. The second group has three identical panels of 2.74-m height, 1.22-m width and 210-mm total depth, namely: BW4, BW5 and BW6. Each group had interior sheathing made of oriented strand board (OSB) type 1R24/2F16/W24 with 11-mm thickness, exterior sheathing made of Canadian Softwood Plywood (CSP) in 5 plies and 15.5-mm thickness, and Spruce-Pin-Fur (S-P-F) Softwood Lumber grade No. 1/2 with 38-mm width located vertically at half the panel width. The panel has two top plates and one bottom plate made of S-P-F lumber. CSP and S-P-F are treated with preservative materials. The wall core was made of expanded polystyrene (EPS) foam type 1. S-P-F was connected mechanically to the sheathing (skin faces) using galvanized nails, while the foam core is connected to the faces using structural adhesive.

The Acceptance criteria for SIPs set forth in ICC-ES AC04 (2004) includes testing three identical panels from each panel size. It also specifies that the average deflection and ultimate load carrying capacity of a panel size will be basically the average of those for the three panels. However, AC04 specifies that when the results of each tested panel vary more than 15% from the average of the three panels, either the lowest test value is used or the average result based on a minimum of five tests may be used regardless of the variations. ASTM E72-10, Standard Test Methods of Conducting Strength Tests on Panels for Building Construction (2010) covers the flexural creep rate for sandwich panels. A typical setup for the flexural creep testing of simply-supported basement wall panel is to load it with a triangular loading. This triangular loading simulates the lateral soil pressure which is specified as an equivalent Fluid Pressure equal to 4.7 kN/m^2 per meter length of the wall as per National Building Code of Canada NBCC Part 9 (2010) for average stable soils. Analogue dial indicators were placed at the maximum bending moment location which was at 0.45 of the panel span. The PWF panels were loaded with solid concrete bricks of 28.6 N (6.44 lbs) and 200x100x60mm dimensions. Bricks were arranged in several layers and incremental piles to produce the intended soil pressure of 4.7 kN/m^2 per meter length of the wall. As such the first panel group was loaded with a total of 20,563.20 N bricks, while the second panel group was loaded with 16,243.00 N. It should be noted that the length of the triangular loading was 2700 mm for the first panel group and 2400 mm for the second panel group, leaving 300 mm length unloaded. This unloaded length represents the wall height between the ground level and the first floor level. Fig. 3 shows views of the triangular loading over the tested panels. Dial gauge readings were recorded at 0 minute before loading, 5 minutes after loading, every 30 minutes for 6 hours after loading, once per day for 30 days, and finally once per week till unloading time. Final readings were taken after unloading for 48 hours. Also Humidity-Temperature sensors were placed near the panels and both humidity and temperature readings were recorded parallel to dial gauge readings. It should be noted that panels BW1, BW2, BW4 and BW5 were at the same environment in the basement of the structures lab, while panels BW3 and BW6 were located in the same basement but in other spot separated by concrete wall from other locations.

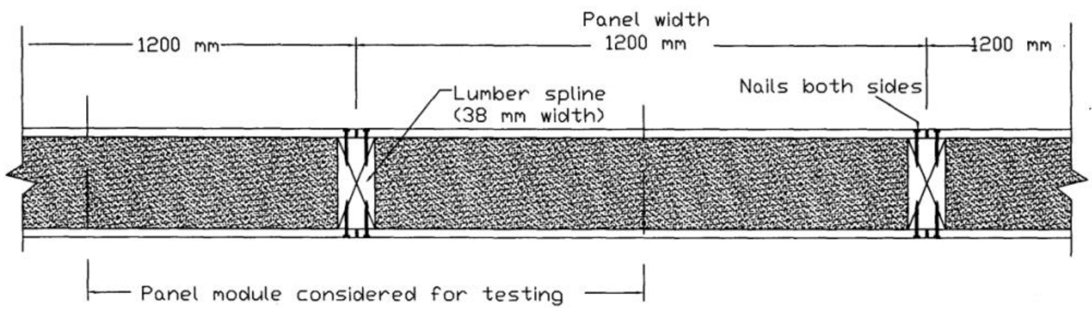


Fig. 2: Typical section at panel lumber-spline connection before and after assembly

Fig. 3: Views of the simulated triangular loading over the panels

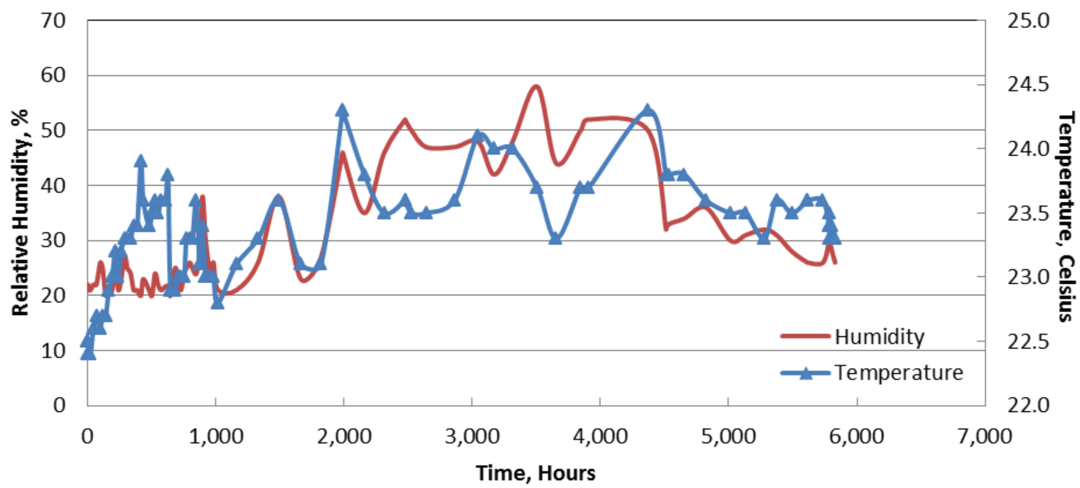


Fig. 4: Recorded temperature and relative humidity with time during creep testing for specimens BW1, BW2, BW4 and BW5

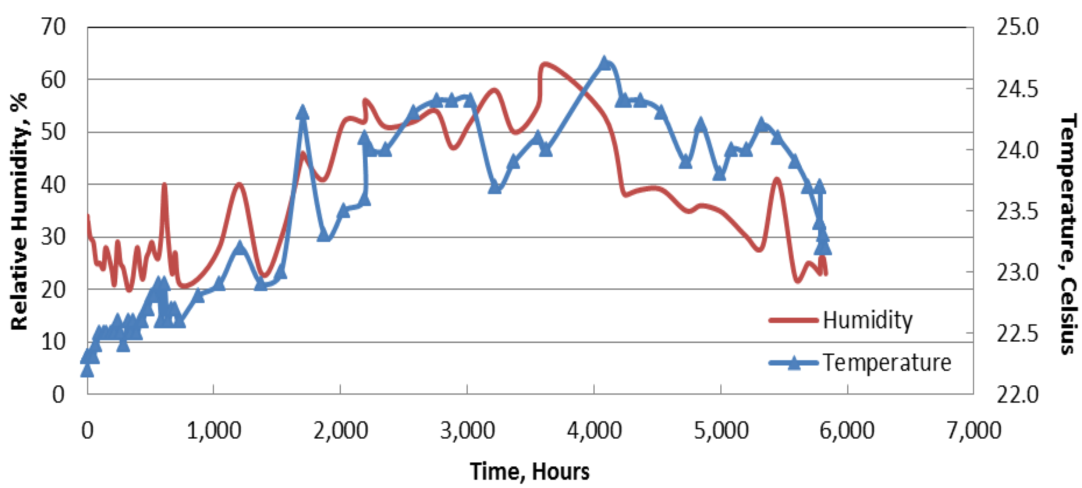


Fig. 5: Recorded temperature and relative humidity with time during creep testing for specimens BW3 and BW6

3 Test Results

Figs. 4 and 5 depict the change in the room temperature and relative humidity during creep test for such panels. It can be observed that room temperature fluctuated between 22ºC and 25 ºC, while the relative humidity ranged between 20 to 70%. The increase in deflection with time for the tested panel groups I and II is shown in Figs. 6 and 7, respectively. Results reported elsewhere (Sayed Ahmed, 2011) showed that the average instantaneous deflection (ID) for both PWF groups was recorded as $\Delta_o = 8.03$ mm at 0.45 of the span after 5 minutes from applying the triangular sustained load. The average final deflection (FD) was recorded as $\Delta_f = 11.12$ mm and $\Delta_f = 10.83$ mm for groups I and II, respectively, after 5785 hours. The average instantaneous recovery deflection (IRD) was 7.26 and 7.68 mm for groups I and II, respectively. The average permanent deflection (PD) was 3.26 and 2.60 mm for groups I and II respectively. Figs. 6 and 7 showed that the long-term creep deflection did not increase smoothly with time due to the cyclic change in temperature and relative humidity over time (Sayed Ahmed, 2011). The following subsections discuss the prediction of flexural creep based in the traditional creep models available in the literature following by the proposed creep model that takes into account the effects of ambient temperature and relative humidity on creep deflection.

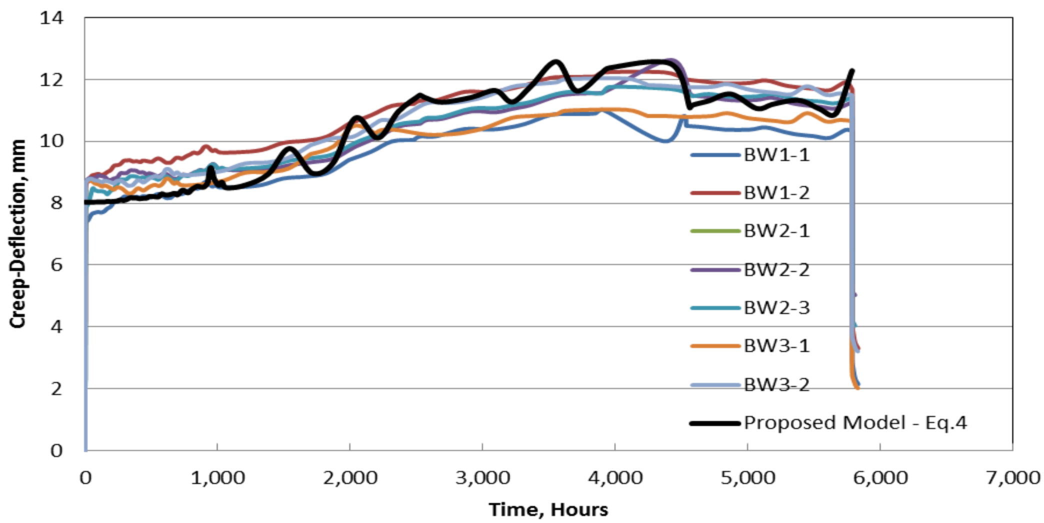


Fig. 6: Proposed Creep Model for Group I

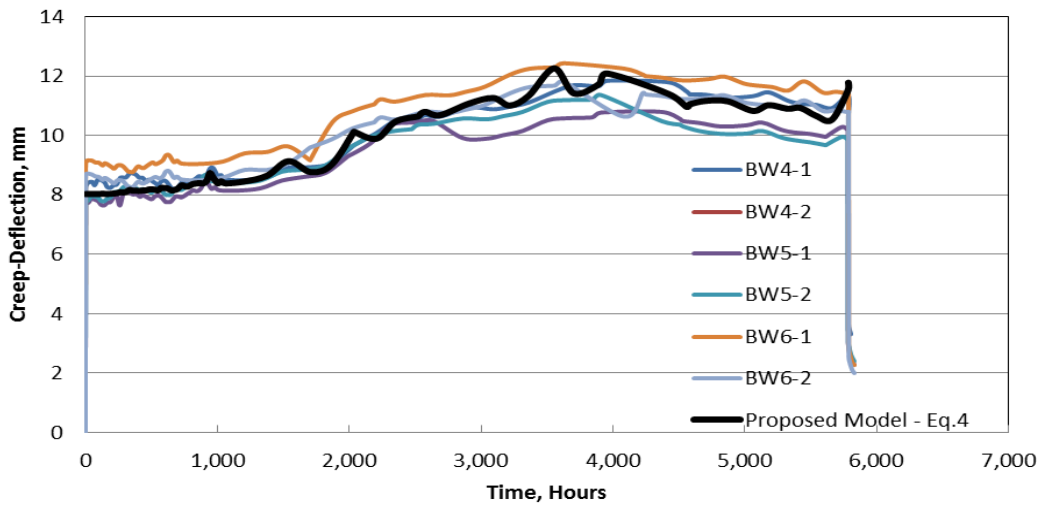


Fig. 7: Proposed Creep Model for Group II

Table 1: Mathematical and Viscoelastic Creep Models (Sayed Ahmed and Sennah, 2012)

Model	Equation
Power	$\Delta_f = \Delta_o + A_1 t^{A_2}$
Logarithmic	$\Delta_f = \Delta_0 + A_1 \ln(t+1)$
Maxwell	$\Delta_f = \frac{\sigma}{A_1}\left(1 + \frac{t\,A_1}{A_2}\right)$
Kelvin	$\Delta_f = A_1\,[1 - \exp(-A_2 t)]$
Standard Linear Solid (SLS) or Zener	$\Delta_f = \Delta_o + A_1(1 - \exp(-\frac{t}{A_2}))$
Burgers	$\Delta_f = \Delta_o + A_1[1 - \exp\ (-A_2 t)] + A_3 t$
Refined Burgers model	$\Delta_f = \Delta_o + A_1(1 - \exp(-A_2 t)) + A_3 t^{A_4}$

Where; Δ (t) = total time dependent deflection; Δ_o = initial deflection; A_i = creep parameters associated with creep deflection equations.

3.1 Traditional Creep Models in the literature

In wood creep includes three distinct types of behavior, which are difficult to separate because they all operate simultaneously. They are time-dependent (viscoelastic) creep, mechano-sorptive (moisture change) creep, and the pseudo-creep and recovery. The initial and short-term creep due to loading obeys the basic model of Hooke's law ($\sigma = E\varepsilon$) where E is the modulus of elasticity, σ is the stress and ε is the strain. The long-term creep response is represented by elastic spring and viscous dashpot, where the plastic deformation obeys Newton's law ($\sigma = \eta \; d\varepsilon/dt$), where dε/dt is the change in strain with time t and η is the viscosity. Table 1 summarizes the mathematical and viscoelastic creep models (rheological models) found in the literature, while Table 2 lists the values of the creep parameter determined from the long-term deflection of the tested panels over the 8 months period (Sayed Ahmed and Sennah, 2012). The R^2 coefficient of determination is a statistics measurement with range $0 < R^2 < 1$ to measure the agreement between the observed and modeled values, where 1 indicates the perfectly fits of the data. The drawback of these traditional creep models is that they do not consider the effect of changes in ambient temperature and relative humidity on flexural creep response. In addition, the corresponding R^2 for both the Kelvin model (rheological model) and Logarithmic model (mathematical model) has negative R^2 value and that couldn't represent the nonlinear behavior of the observed data.

Table 2: Creep Parameters from Nonlinear Regression Analysis

Type of Model	R^2	SSE	Creep Parameters			
Name			A_1	A_2	A_3	A_4
Group I						
Power	0.93	7.47	0.02193	0.58903	NA	NA
Logarithmic	-1.176	52.57	0.25903	NA	NA	NA
Maxwell	0.91	9.24	8.53103	7.2E-05	NA	NA
Kelvin	-4.496	95.91	9.68342	1.85649	NA	NA
Zener (SLS)	0.94	7.31	3.97744	0.00038	NA	NA
Burgers	0.92	10.15	4.912762	0.0002242	0.00001	NA
Refined Burgers	0.95	5.44	4.28	0.00026	0.28	0.001
Proposed Equation 4	0.869	26.15	3.184	1084.99	0.53576	0.37108
Group II						
Power	0.86	16.8	0.004357	0.780337	NA	NA
Logarithmic	-3.67	86.267	0.232536	NA	NA	NA
Maxwell	0.84	18.33	8.257541	7.72E-05	NA	NA
Kelvin	-13.84	130.26	9.491888	0.896888	NA	NA
Zener (SLS)	0.884	14.022	4.916055	0.000224	NA	NA
Burgers	0.89	14.1	4.912762	0.0002242	0.00001	NA
Refined Burgers	0.88	14.05	4.920284	0.000224	0.01	0.000981
Proposed Equation 4	0.942	9.7	3.46244	1084.992	0.52659	0.341964

NA: not applicable; R^2: coefficient of determination with value range (0 – 1); SSE: summation of square of errors

3.2 Proposed Viscoelastic Creep Model and Humidix Effect

Wood is hygroscopic organic material that adsorbs and losses moisture from surrounding air to be in equilibrium with surrounding different environmental conditions that could be dry, wet, hot, corrosive vapour, or combination of some of them. Its service condition is considered to be dry condition when the average equilibrium moisture content (EMC) is 15% or less than 19%. The *Humidex* is a Canadian index to describe the weather feeling to the average person, where it is a combination of temperature and relative humidity in percentage as in Equation 1 (Masterton and Richardson, 1979). Equation 2 considers the direct environmental influences on creep which affects the PWF under load. The changes in moisture and temperature in PWF are essentially a diffusion process so that any change introduces gradients. These gradients induce stresses which are accompanied by creep, and it follows that the moisture and temperature deformations are not really independent of stress by including creep deformation.

[1] $$Humidex = Air\ Temperature\ in\ Celsius + Relative\ Humidity\ in\ \%$$

To understand the effect of Humidex on creep deflection, the following equation was considered.

[2] $$c_H = a\ H + b$$

Where H = Humidex; c_H = creep at a Humidex H; a and b are Humidex constants. Figs. 6 and 7 depict the effect of the *Humidex* on the total creep deflection of the tested panel group I and II, respectively. A statistical package for curve fit was used to determine the Humidex constants a and b and plot the developed equations with the experimental data in Figs. 6 and. It can be observed that the creep rate increases with increase in the ambient temperature and relative humidity (i.e. with increase in *Humidex*), as expected. During creep tests, it was observed that the room temperature ranged from 22 and 25^{o}C, while the relative humidity ranged from 20 to 70% as shown in Figs. 4 and 5. The Humidex (H = Temperature + Humidity) varied between 42 and 92 as depicted in Figs. 8 and 9.

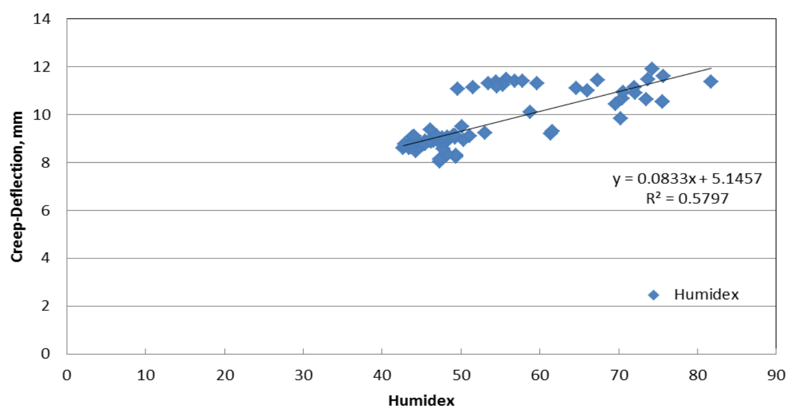


Fig. 8: Effect of Humidex on creep displacement for tested panels BW1, BW2, and BW3

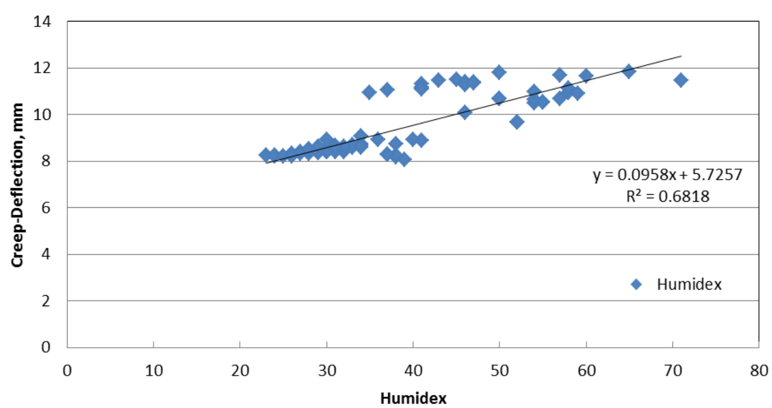


Fig. 9: Effect of Humidex on creep displacement for Tested Panels BW4, BW5,and BW6

Humidex affects creep through two phenomena: a change in the rate of creep of dry wood-based materials with Humidex, and a change in the properties of wood-based materials with Humidex. Polivka and Best (1960) suggested that the temperature-sensitivity of creep can be explained in terms of Arrhenius activation energy equation since the secondary creep is a thermal activated process. Browne and Blundell (1969) modified the Arrhenius model to look as Equation 3. In the current research, the authors developed the Arrhenius equation as shown in Equation 4 to take into account the effect of Humidex (temperature and relative humidity) over time.

[3] $$n(t) = a\,\sigma\,e^{-U/R\tau_a}$$

[4] $$\Delta_{f,t} = \Delta_0 + A_1\,L\,e^{-A_2/A_3(T+\theta)t^{A_4}}$$

Where n = specific creep rate, σ = applied stress, U = activation energy, R = medium constant, τ_a = absolute temperature, a = constant, Δ_o = instantaneous deflection ($\Delta_o = \sigma/E$), A_1, A_2, A_3, A_4 = creep constants, L = applied load equal to the constant of 4.7 (obtained from 4.7 kN/m^2/meter depth), T = temperature, θ = relative humidity, t = time, n = constant, and $\Delta_f(t)$= final deflection.

Using the Excel Solver with the Generalized Reduced Gradient (GRG) algorithm to minimize the summation square of error to obtain the creep constants A_1, A_2, A_3 and A_4 were determined for each panel group as shown in Table 2. Figs. 6 and 7 depict the predicted creep deflection using the proposed equation against the recorded deflections from all dial gauges for each panel. The ratio between panel deflection after a period of time, $\Delta_f(t)$, to the short term deflection (instantaneous deflection, Δ_o) is expressed in Equation 5 in terms of flexural creep constant (K).

[5] $$K = (\Delta_{f,t}/\Delta_o) - 1$$

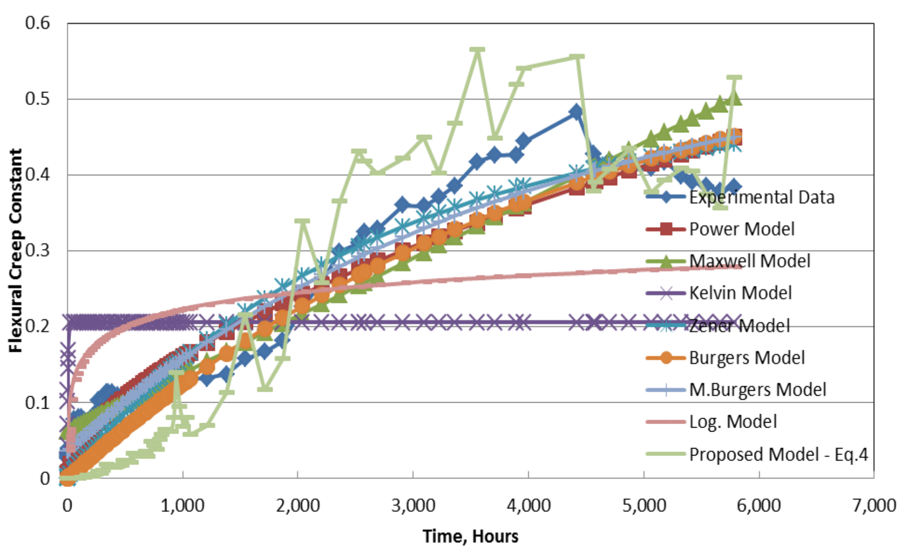


Fig. 10: Measured and predicted Flexural Creep Constant (K) versus time for Group I

Figures 10 and 11 showed correlation between the measured and predicted flexural creep Constant (K) versus time for Groups I and II, respectively. It can be observed that the proposed model, that takes into account the changes in temperature and relative humidity during the creep test, showed good agreement with the average deflection recorded for each panel group. Figures 10 and 11 also show the correlation between the traditional creep models listed in Table 1 with the average creep deflection history over the 8-month period of the creep test. It can be observed that Maxwell, Refined Burgers and Burger models provides good correlation with the average creep deflection history in contrast to other traditional models listed in Table 1 if the change in temperature and relative humidity is neglected. The R^2 for the proposed model was originally above the 0.9 for both groups for the observed data during the experimental period. The extended curve beyond the experimental data up to 75 years was adjusted to the average laboratory temperature and relative humidity which reduced the R^2 for both groups. As seen in Fig. 12, the flexural creep constant has higher rate in the first 5 years followed by low creep rate.

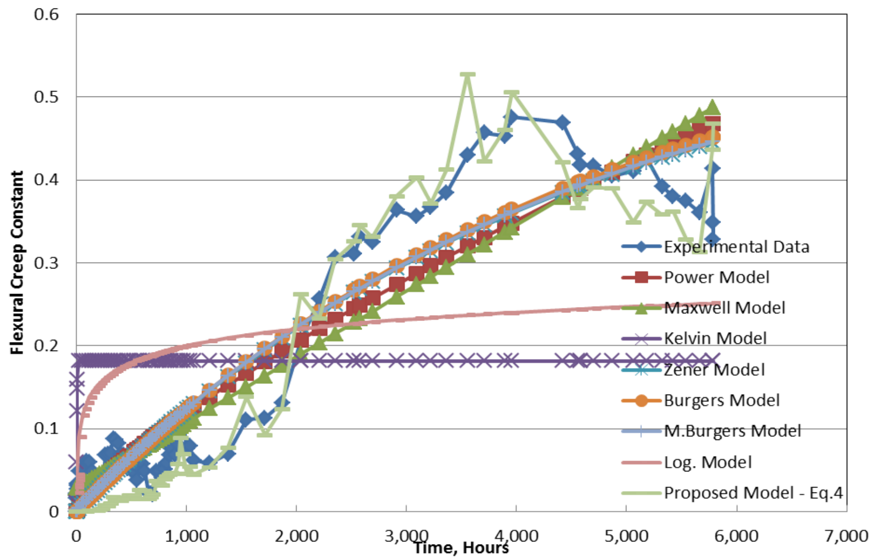


Fig. 11: Measured and predicted Flexural Creep Constant (K) versus time for Group II

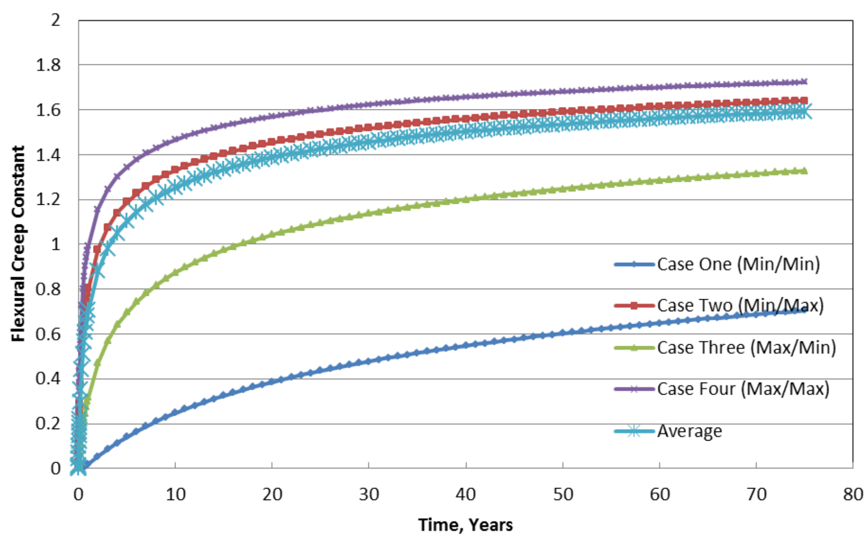


Fig 12: Climate Effect on Long-term Flexural Creep Constant

One of the merits for the proposed model is its ability to predict the flexural creep constant under the effect of climatic change. Figure 12 depicts five different climatic load cases for Toronto City in Ontario that accounts for the variation of temperature and relative humidity over the time up to 75 years. Case 1 (Min/Min) predicts the creep constant for constant ambient temperature of relative humidity of 0^oC and 20%, respectively, over 75 years. While Case 2 (Min/Max) predicts the creep constant for constant ambient temperature and relative humidity of 0^oC and 100%, respectively. Case 3 (Max/Min) represents constant temperature and relative humidity of 30^oC and 20%, respectively. The constant temperature and relative humidity for case 4 (Max/Max) are 30^oC and 100%, respectively. It should be noted that the annual average temperature and relative humidity in Toronto can be given as 26.5^oC and 61.1%. From

Fig. 10, it can be observed that the flexural creep constant for the second tested panel group after 75 years is predicted to be 0.705, 1.641, 1.328, 1.723 and 1.593 for the five climatic load cases mentioned above. It is also noted that under the average room temperature and relative humidity of 21.97^{o}C and 38.58% respectively, the predicted flexural creep deflection after 75 years is 1.43, which matches with results obtained from the Burgers Model.

4 Conclusions

Based on the experimental and theoretical findings, it can be observed that mathematical Power model and the rheological creep models for Maxwell, Zener, Burgers and Refined Burgers agreed well with the experimental data along with the proposed model that takes into account the *Humidex* effect over the 8-month creep test period reported in this paper. The proposed model in this paper predicts the creep deflection constant after 75 years as 1.43 for the average readings of the temperature and relative humidity during the tested period. It is recommended to conduct creep tests on PWF panels beyond the 8-month period to validate the proposed creep model over a considerable number of years.

Acknowledgements

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