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# Creep behavior of 3D core wood-strand sandwich panels

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**Abstract:** A preliminary experimental evaluation of duration of load and creep effects of lightweight wood-strand sandwich panels (lwW-SSP) was conducted following ASTM D6815-09 to determine the equivalence to the duration of load and creep effects of visually graded lumber as specified in Practice D245. The modulus of rupture (MOR) of lwW-SSP was obtained using four-point bending tests to evaluate their creep and load behavior at three stress levels (15, 40 and 65% of MOR). Two different widths were considered to observe the effect of this parameter. lwW-SSP preformed well under long-term loads, as tertiary creep was not observed at all stress levels and the strain rate decreased over time. The panels met the criteria specified in the standard. None of the specimens failed, the creep rate decreased and the fractional deflection was <2. Accordingly, the duration of load factors of visually graded lumber is applicable to these panels. For the theoretical evaluation of solid wood behavior, viscoelastic models can also be applied to describe the creep behavior of lwW-SSP with wood-strand corrugated cores. An exponential viscoelastic model consisting of five elements accurately approximates the experimental creep behavior of three-dimensional (3D) core sandwich panel.

**Keywords:** bending creep, corrugated core, duration of load, sandwich panel, viscoelasticity, wood strand composite

## Introduction

Creep behavior of building products, such as floor or roof sheathing materials, is an important characteristic. Sandwich panels have been developed for building construction, such as structural insulated panels, that consist of an insulating core sandwiched between the outer facings [typically oriented strand boards (OSB)]. Structural insulated panels account for 1% of the construction market in the US (Gagnon and Adams 1999). Another example is three-dimensional (3D) fiberboard core panels which are manufactured by means of a wet process (Hunt and Winandy 2003). A recent development in this product family is a wood-strand sandwich panel (W-SSP) engineered from wood-strand outer plies and a 3D wood-strand core (Figure 1a) (Voth et al. 2015). Wood-based composite panels, inlcuding W-SSPs, were submitted to extensive testing and evaluation (Weight and Yadama 2008a,b; Voth 2009; Shalbafan et al. 2013; Smardzewski 2013; Voth et al. 2015; Li et al. 2016; Way et al. 2016; Smardzewski and Jasińska 2017) and were found to be at least as good as OSB as a sheathing material, if used for walls, floors and roofs. A systematic method to design the geometry of the core is being currently developed based on finite element analysis, serviceability, and knowledge of wood-strand conformance necessary for molding based on past experience (Wang 2012). This task is challenging because all wood-based materials are viscoelastic in nature, and it is critical to evaluate their time-dependent behavior.

Under load, wood deforms elastically initially followed by an additional time-dependent deformation which is known as creep, which undergoes three stages. In the primary creep, the strain rate is relatively high, but slows down with time. In the secondary creep or steady-state creep, the strain rate eventually reaches a minimum and becomes nearly constant. In the tertiary creep, the strain rate increases exponentially with time, and may eventually lead to failure, which is called creep rupture. Creep can occur even at very low stress levels. The time-dependent behavior is influenced mainly by the relative humidity (RH) and temperature (T) (Alvarez et al. 2004). These factors, on the other hand, influence the moisture content (MC) of wood-based materials, while creep increases with MC because water is a plasticizing agent (Bodig and Jayne 1982). Similarly, increasing T alone also expedites the creep process (Schniewind 1968; Holzer et al. 2007). Viscoelastic models describe well the time-dependent behavior of materials (Bodig and Jayne 1982; Holzer et al. 2007), which can be predicted by fitting empirical equations to the experimental data obtained from

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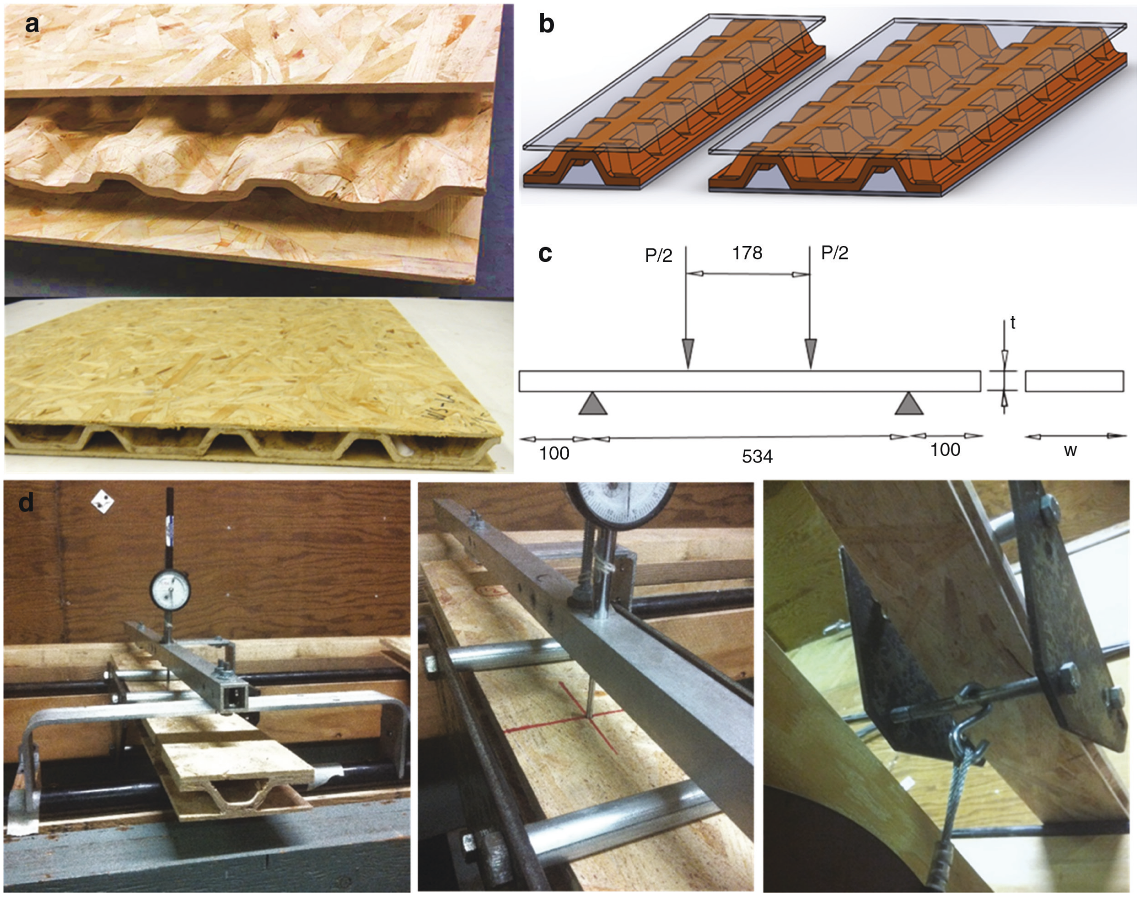


**Figure 1:** W-SSP construction details, test specimen configurations, and bending creep test set-up: (a) W-SSP and its components, (b) schematic configuration of narrow and wide specimens, (c) loading configuration (dimensions in mm) and (d) flexure set-up of creep test.

short-term creep testing (Naumenko and Altenbach 2007). In the present study, four viscoelastic models were applied to describd the creep behavior of sandwich panels, namely standard, Burger, exponential and power law models (Cai et al. 2007; Naumenko and Altenbach 2007).

In the case of applications of thin-walled hollow-core W-SSPs in building envelope constructions, it is essential to evaluate their creep and relaxation behaviors when they are subjected to constant load over time, such as in flooring and roofing applications. Such evaluations are time consuming and expensive. The ASTM D6815 (ASTM 2009) standard provides a procedure that is supposed to be an engineering equivalence to the duration of load and creep effects obtained by visual grading of lumbers as specified in Practice D245 (ASTM 2011), which is applicable for products used under dry service conditions.

The objectives of the preliminary analyses described in the present paper are to demonstrate the equivalence to the Practice D245 procedure to the load/time relationship. More precisely, W-SSPs should be submitted to a 90-day creep-rupture test and it should be observed whether the panels satisfy the following criteria: (1) adequate strength over a 90-day period, (2) decreasing creep rate and (3) limited fractional deflection. Moreover, the effectiveness of viscoelastic models in general should be investigated, which can also be applied to other wood-based panels. According to the standard procedure, the parameters 50% RH and 23°C will be maintained constant.

## Materials and methods

Outer flat plies and 3D core layers were manufactured to a target density of 640 kg $m^{-3}$ by hot-pressing resinated lodgepole pine wood strands with a typical phenol formaldehyde (PF) adhesive (Hexion Specialty Chemicals, Springfield, OR, USA). Subsequently, two flat plies were bonded with modified polyisocyanate (MDI) adhesive (Daubond U6000 series, Daubert Chemical Company, Chicago, IL, USA) at room temperature (rT) to each of the 3D cores to fabricate sandwich panels (74 cm×74 cm). A full description of the fabrication process is explained in Voth et al. (2015), Voth (2009) and Weight and Yadama (2008a,b). Five specimens were cut from each panel in the longitudinal

(L) direction, four of which were narrow specimens (about 105 mm) and one a wide specimen (about 210 mm), as shown in Figure 1b.

One of the narrow specimens from each panel was tested in flexure following ASTM D 7249 (ASTM 2006) standard using the 2 kip Instron test frame, Model 4466, to determine its flexural strength [modulus of rupture (MOR)]:

$$\sigma = \frac{My}{I}, \tag{1}$$

where $M$, $y$ and $I$ are maximum moment due to bending load at the point of rupture, distance from the neutral axis and moment of inertia, respectively. In this study, applied load is defined as a fraction of the maximum bending load obtained from a flexure test. MOR is proportional to the bending load, and cross-sections, which are the same for both creep and flexural test specimens; therefore, creep load can be calculated as a fraction of the maximum bending load mentioned in Table 1.

**Table 1:** Specimen dimensions and static bending test results.

| | Width (mm) | Thickness (mm) | Span length (mm) | Max. load (N) |
|---|---|---|---|---|
| Mean | 103.8 | 33.2 | 560 | 4153 |
| SD | 2.08 | 0.75 | – | 239 |
| COV (%) | 2.0 | 2.3 | – | 5.75 |

COV, Coefficient of variation.

**Table 2:** Specimen dimensions for the four-point bending creep test.

| Group loading level | Mean | SD | COV (%) |
|---|---|---|---|
| (1) 15%; 623 N | | | |
| Width (mm) | 105.8 | 1.02 | 0.96 |
| Thickness (mm) | 33.3 | 0.28 | 0.83 |
| (2) 40%; 1661 N | | | |
| Width (mm) | 104.1 | 1.09 | 1.05 |
| Thickness (mm) | 33.7 | 0.66 | 1.96 |
| (3) 65%; 2700 N | | | |
| Width (mm) | 105.2 | 1.8 | 1.71 |
| Thickness (mm) | 33.9 | 0.13 | 0.38 |
| (4) 15%; 1246 N | | | |
| Width (mm) | 211.3 | 4.58 | 2.17 |
| Thickness (mm) | 33.6 | 0.58 | 1.73 |

The remaining three narrow specimens out of the four were tested for their creep behavior in flexure as per ASTM D6815 (ASTM 2009) standard at the stress levels of 15, 40 and 65% of MOR. The wider specimen was evaluated at the 15% stress level. A total of 16 specimens were submitted to a bending creep test (dimensions are listed in Table 2).

**Experimental procedure and acceptance criteria:** All the specimens were kept at 23°C/50% RH. The four-point bending test was applied (Figure 1c). Deflection at mid-span relative to the supports was measured by means of a dial gauge (Figure 1d). To achieve a desired stress level, the necessary load was applied to the specimen by hanging it on the hook (Figure 1d). The bending deflection was measured immediately after the load application at different time intervals: 1, 3 and 5 min and 1, 2, 3 and 24 h and once every week for 90 days.

The W-SSPs must fulfill the three aforementioned criteria to be the engineering equivalent concerning the duration of load and creep effects of visually graded lumber under dry conditions: (1) The total number of failures after 90 days shall be less than the critical order statistic value, which for this study is defined as 1, because <28 specimens are tested. This means that no failures shall occur at the end of the test period. (2) Creep rate, defined as the change in creep deflection per 30 days, for each specimen should be decreasing:

$$D_{30} - D_i > D_{60} - D_{30} > D_{90} - D_{60}, \tag{2}$$

where $D_i$ is the initial deflection that is taken at ca. 1 min after applying a constant load. $D_{30}$, $D_{60}$ and $D_{90}$ are, respectively, deflections measured on the 30$^{th}$, 60$^{th}$ and 90$^{th}$ day. This condition is to assure that the creep rate is decreasing over time and that the specimens do not exhibit any signs of tertiary creep. (3) The fractional deflection for each specimen, that is the ratio of total deflection to the initial deflection, must meet the following condition:

$$FD_{90} = \frac{D_{90}}{D_i} \leq 2. \tag{3}$$

**Viscoelastic models:** The models generally include a combination of elastic spring(s) and viscous dashpot(s) (Figure 2) (Cai et al. 2007). Equations of the presented models in Figure 2 are defined in Table 3, where $U$ is the deflection at mid-span of the specimen; $P$ is the constant bending load for a period of time $t$; $k_1$, $k_2$ and $k_3$ are elastic spring constants and $r_1$ and $r_2$ are viscosity of dashpots. In addition, a, b, c, m and n are coefficients which are determined by the least square method. The power law model is another viscoelastic model that has been effective in characterizing creep behavior (Bodig and

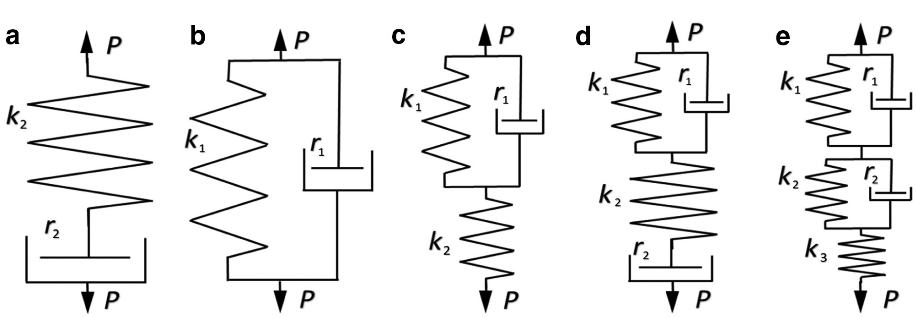


**Figure 2:** Typical viscoelastic models that are a combination of elastic spring(s) and viscous dashpot(s) to approximate experimental creep results: (a) Maxwell, (b) Kelvin, (c) standard, (d) Burger and (e) exponential (Cai et al. 2007; Plenzler and Miler 2009).

**Table 3:** Associated equations of viscoelastic models in Figure 2.

| Model | Equation |
|---|---|
| Maxwell (two parameters) | $U=\frac{P}{k_2}+\frac{P}{r_2}t$ |
| Kelvin (two parameters) | $U=\frac{P}{k_1}\left(1-\exp\left(-\frac{k_1}{r_1}t\right)\right)$ |
| Standard (three parameters) | $U=\frac{P}{k_1}\left(1-\exp\left(-\frac{k_1}{r_1}t\right)\right)+\frac{P}{k_2}$ |
| | Simplified: $U=a+b(1-\exp(-mt))$ |
| Burger (four parameters) | $U=\frac{P}{k_1}\left(1-\exp\left(-\frac{k_1}{r_1}t\right)\right)+\frac{P}{k_2}+\frac{P}{r_2}t$ |
| | Simplified: $U=a+b(1-\exp(-mt))+ct$ |
| Exponential (five parameters) | $U=\frac{P}{k_1}\left(1-\exp\left(-\frac{k_1}{r_1}t\right)\right)+\frac{P}{k_2}\left(1-\exp\left(-\frac{k_2}{r_2}t\right)\right)+\frac{P}{k_3}$ |
| | Simplified: $U=a+b(1-\exp(-mt))+c(1-\exp(-nt))$ |

Jayne 1982; Cai et al. 2007). It is defined as: $U=P/k+(P/r)t^n$, simplified $U=a+bt^n$ (Eq. 4), where $P/k$, $P/r$ and $n$ are model parameters (Cai et al. 2007). In this study, the following models were chosen: standard, Burger, exponential and power law models, to approximate the experimental creep behavior.

## Results and discussion

Based on the average results of the four-point bending test shown in Figure 3, MOR of this sandwich panel was computed to determine the three loading levels for performing the creep test. One of the specimens at the 65% loading level ruptured during the set-up process because of the uneven stress; therefore, only three specimens were loaded. Examining the variation in the deflection behavior of specimens subjected to the same stress level (Figure 4a and b) demonstrates the inherent variability that can be expected in the composite material due to the variation in the panel horizontal density and bond performance from point to point (Sumardi et al. 2007). In the figures, group numbers are associated with different stress levels: Group 1 (15%), Group 2 (45%), Group 3 (65%) and Group 4 (wide specimens, 15%). Note that all specimens at all stress levels exhibit only the primary and secondary creep behavior during the 3-month testing period, and none of them exhibit the tertiary creep followed by failure. Accordingly, the 3D core W-SSPs meet the first acceptance criterion, i.e. the total number of failures after 90 days is <1.

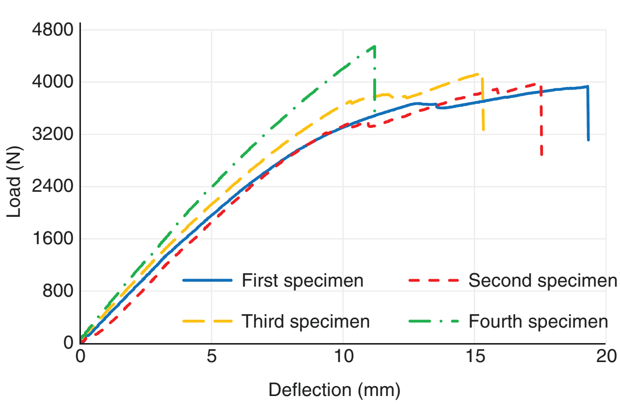


**Figure 3:** Static bending test results of narrow specimens to obtain MOR.

To further examine the deflection changes over time, the mean value at each time period with error bars is plotted in Figure 4c. As expected, the strain rate (slope of deflection-time curve) in the primary and secondary stages increase with increasing stress levels. In specimens loaded at 65% stress level (Group 3), the strain rate in the secondary stage is higher than that at lower loading levels, but it stabilizes over time and reaches a decreasing strain rate. Negligible differences between deflection curves at 15% stress level for both narrow and wide specimens indicate that the creep behavior of 3D core W-SSPs does not vary significantly based on the number of ribs included in the width direction of the specimen. The results from this study can be extended to wider specimens as well. This confirms our expectations in a manner similar to White (2011), who concluded that additional ribs do not have any effect on the bending stiffness of the 3D core W-SSPs.

The creep rates calculated in Table 4 and presented in Figure 4d indicate that the creep rate at all stress levels is decreasing and satisfies the second acceptance criterion as formulated in Eq. (2). In addition, decreasing creep rates for all stress levels after 90 days confirm the reliability and performance of these lightweight W-SSPs (lwW-SSPs) as potential sheathing materials in building envelopes. The fractional deflection values of all groups given in the last column of Table 4 show that all computed fractional deflections are <2, thus satisfying the third acceptance criterion of the aforementioned standard specification.

Accordingly, the engineering equivalence is established in terms of the duration of load and creep effects of visually graded lumber as specified in Practice D245. Therefore, the relation of strength to the duration of load given in Practice D245 can be used to modify the allowable stress of these W-SSPs. In addition, the duration effect is not more severe than that represented by the accepted model for structural lumber, and therefore, the duration of load factors in the

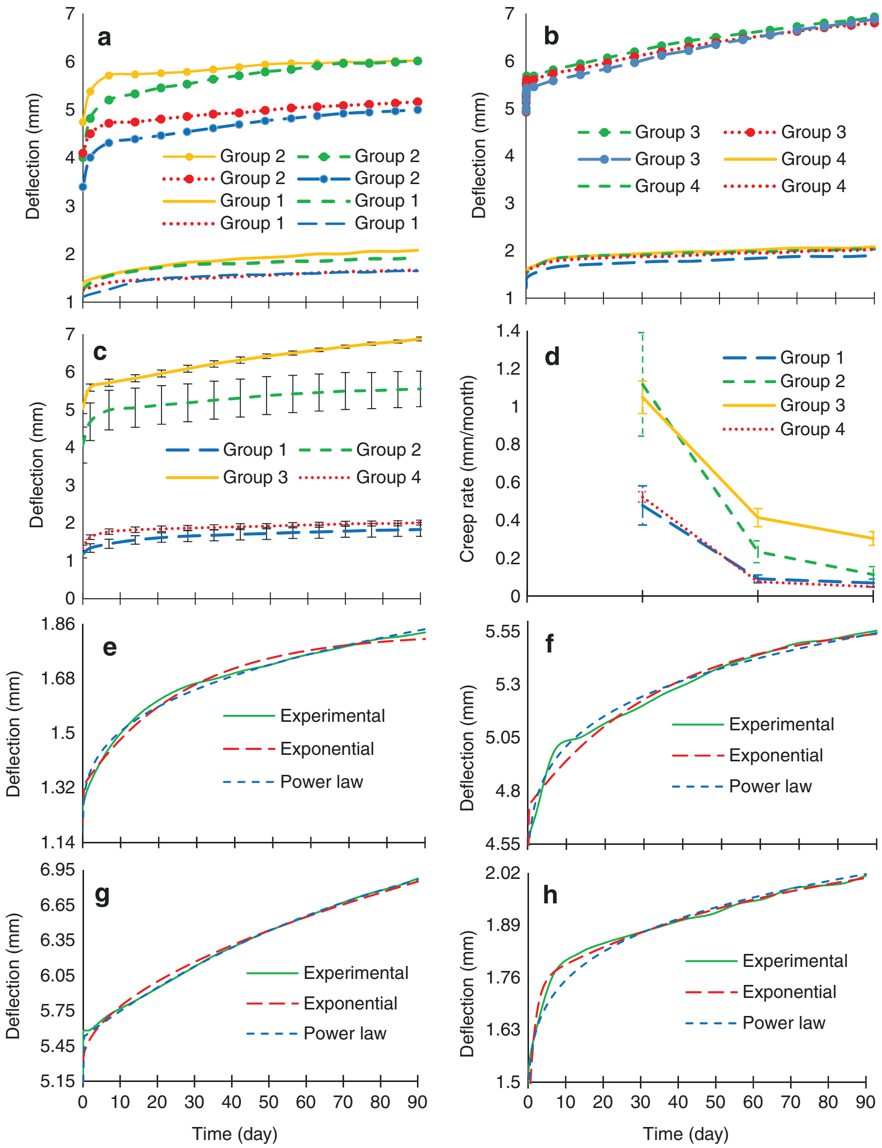


**Figure 4:** Experimental creep deflection vs. time: (a) Groups (Gr.) 1 and 2, (b) Gr. 3 and 4, (c) average deflection for all groups, (d) creep rate and comparison between experimental data and viscoelastic models, (e) Gr. 1, (f) Gr. 2, (g) Gr. 3 and (h) Gr. 4.

**Table 4:** Creep rates and fractional deflection values of all groups [note that standard deviation (SD) refers to the sample SD].

| Group<br>Str. level | Data | $D_{30}-D_i$ (mm) | $D_{60}-D_{30}$ (mm) | $D_{90}-D_{60}$ (mm) | $D_{90}/D_i$ |
|---|---|---|---|---|---|
| Gr. 1 | Mean | 0.479 | 0.092 | 0.069 | 1.56 |
| 15% | SD | 0.103 | 0.21 | 0.021 | 0.095 |
| | %COV | 21.55 | 22.61 | 30.15 | 6.07 |
| Gr. 2 | Mean | 1.118 | 0.235 | 0.114 | 1.38 |
| 40% | SD | 0.273 | 0.058 | 0.042 | 0.111 |
| | %COV | 24.43 | 24.62 | 36.85 | 8.09 |
| Gr. 3 | Mean | 1.050 | 0.415 | 0.305 | 1.35 |
| 65% | SD | 0.086 | 0.048 | 0.036 | 0.029 |
| | %COV | 8.22 | 11.54 | 11.79 | 2.10 |
| Gr. 4 | Mean | 0.524 | 0.076 | 0.051 | 1.5 |
| 15% | SD | 0.027 | 0 | 0 | 0.043 |
| (2W) | %COV | 5.25 | 0 | 0 | 2.85 |

**Table 5:** Parameters of viscoelastic models obtained by approximation of experimental data in this study.

| Group | Model | a | b | c | m | n | $R^2$ |
|---|---|---|---|---|---|---|---|
| Gr. 1 | Standard | 1.2311 | 0.5676 | – | 0.0529 | – | 0.985 |
| 15% | Burger | 1.2206 | 0.3635 | 0.0029 | 0.1296 | – | 0.993 |
| | Expon | 1.1930 | 0.5044 | 0.1311 | 0.0371 | 6.4577 | 0.996 |
| | Power law | 1.1751 | 0.1588 | – | – | 0.3191 | 0.997 |
| Gr. 2 | Standard | 4.3377 | 1.1190 | – | 0.0714 | – | 0.928 |
| 40% | Burger | 4.1213 | 0.7866 | 0.0082 | 7.5722 | – | 0.980 |
| | Expon | 4.1153 | 0.6097 | 0.8824 | 11.790 | 0.0283 | 0.994 |
| | Power law | 4.0439 | 0.6115 | – | – | 0.1992 | 0.991 |
| Gr. 3 | Standard | 5.3818 | 1.8058 | – | 0.0181 | – | 0.958 |
| 65% | Burger | 5.1623 | 0.4819 | 0.0145 | 19.2679 | – | 0.988 |
| | Expon | 5.0266 | 0.4971 | 2.1093 | 294.889 | 0.0112 | 0.998 |
| | Power law | 5.3194 | 0.1350 | – | – | 0.5395 | 0.986 |
| Gr. 4 | Standard | 1.4022 | 0.5367 | – | 0.1508 | – | 0.950 |
| 15% | Burger | 1.3860 | 0.4027 | 0.0026 | 0.4784 | – | 0.982 |
| (2W) | Expon | 1.3376 | 0.3165 | 0.3528 | 5.6391 | 0.0342 | 0.992 |
| | Power law | 1.2945 | 0.2850 | – | – | 0.2068 | 0.986 |

National Design Specification (NDS) can be used. However, it is important to realize that this equivalency does not provide a duration of load factor specific for the W-SSPs.

Applying the models listed in Table 3, the experimental creep behavior of different groups was modeled and the corresponding model parameters were determined using the least square method (Table 5). The coefficient of determination, $R^2$, indicates an excellent fit between the model prediction and the experimental data. Based on the $R^2$ values, the exponential and power law models fit the experimental data the best, as also illustrated in the plots in Figure 4e–h. Although the difference between the coefficients of determination for these two models is small, it is observed that the exponential viscoelastic model fits the experimental data better than the power law model in all groups, except the first one.

## Conclusion

A preliminary evaluation of the creep behavior of 3D core W-SSPs was conducted following ASTM D6815-09 to determine the equivalence to the creep effect and the duration of load relationship for visually graded solid wood as specified in Practice D245. Three different stress levels (15, 40 and 65% of MOR) and two different specimen geometries (small and broad) at one stress level were considered. The results successfully demonstrate the equivalency to the Practice D245 duration of load relationship through a 90-day evaluation, while the following criteria are satisfied: adequate strength over a 90-day period, decreasing creep rate and limited fractional deflection. Additionally, analysis shows that the viscoelastic models, generally applied to predict the creep behavior of other wood-based materials, accurately characterize the creep behavior of W-SSPs tested in this study. Therefore, the duration of load factors of lumbers mentioned in Practice D245 can be used for the W-SSPs with corrugated cores.

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