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Creep and Creep–Rupture Behavior of Wood-Based Structural Panels

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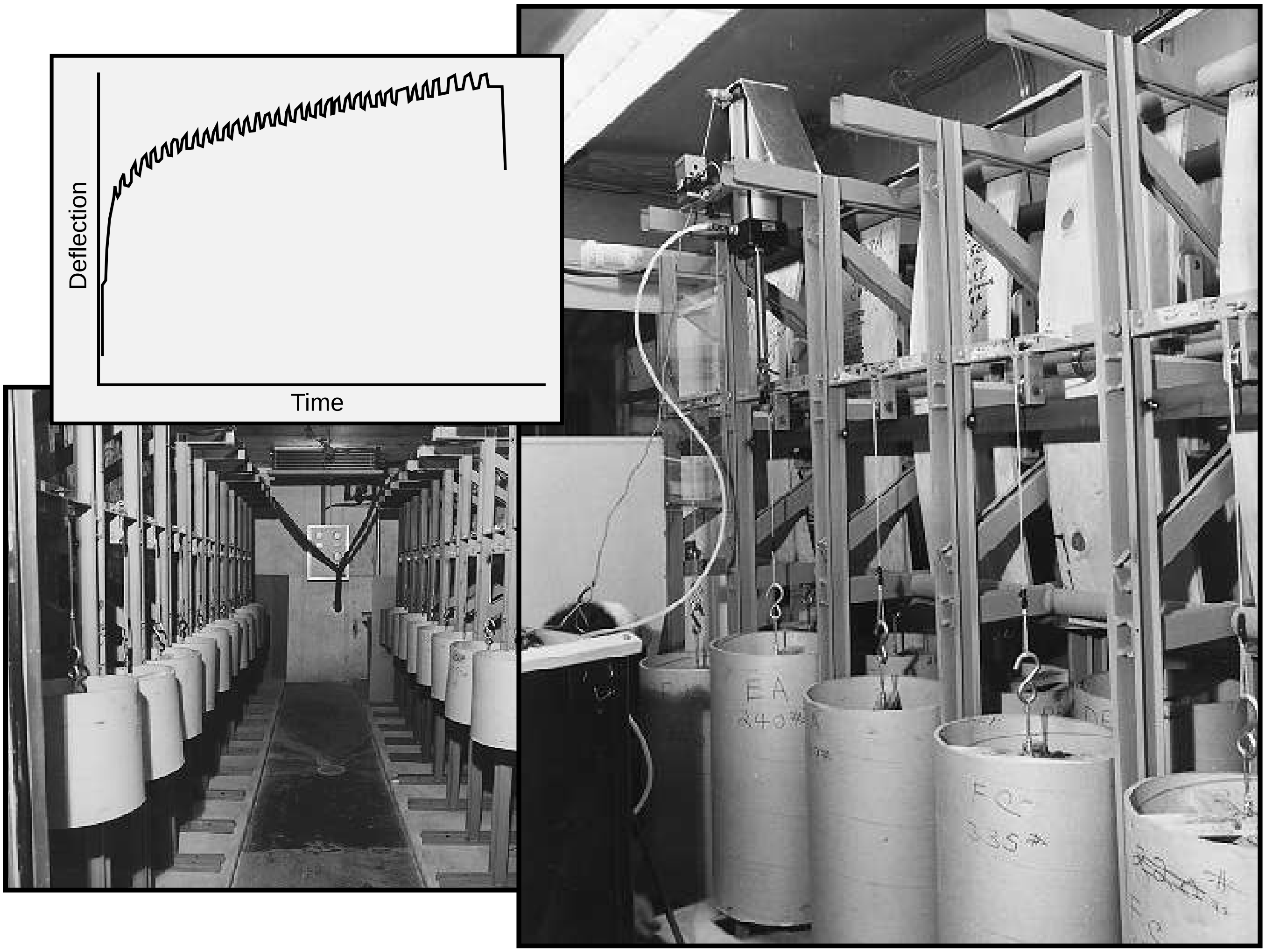

Abstract

This paper summarizes a cooperative research program between the USDA Forest Service, Forest Products Laboratory (FPL), in Madison, Wisconsin, and Forintek Canada Corp. in Vancouver, British Columbia, Canada. This research program provided detailed creep–rupture and some creep information for composite panel products. Commercially produced plywood, oriented strandboard (OSB), and minimally aligned waferboard were tested to identify nine mills (three for each product) that produced panels with a range of flexural creep performance. The three plywood, three OSB, and three waferboard products (nine products total, one from each mill) were then tested to provide information on their duration of load (DOL) and creep performance. Large panel specimens were subjected to both ramp-load and constant-load tests under one environmental condition. The constant-load results provided conventional or deterministic DOL factors that compared favorably with National Design Specifications recommended for adjusting lumber design strength properties under dry service conditions. Ramp-load specimen data generally indicated a lower rate of damage accumulation than did data for constant-load specimens. Creep tests at two low constant-load levels were also performed on large specimens under three environmental conditions for a 6-month period. Those results suggested that present deterministic creep factors in panel design practice might be acceptable for plywood under the influence of relatively severe conditions, for OSB in moderate conditions, and for waferboard in dry service environmental conditions.

Keywords: composite panel products, creep, duration of load, plywood, oriented strandboard, environmental effects.

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Introduction

The need for engineering data on wood-based panel products necessarily extends beyond the determination of static strength and stiffness properties. The emergence of allowable design values for structural panels and the imminent use of reliability-based design methods (O'Halloran and Elias 1988) require the adjustment of strength and stiffness values obtained from short-term laboratory tests to values that will assure a specified level of structural safety under the loads and environments encountered during the life of the structure. To fulfil that general objective requires knowledge of the materials' short-term mechanical properties, the effects of load history, and the effects of thermal and moisture conditions during service.

One of the better known aspects of designing with wood or wood-based products is that the strength of these products is dependent on time under stress. Many scientists have studied this phenomenon, known traditionally as the duration of load (DOL) effect, and have devised many methods of testing and modeling it. Load duration effects, specifically applied to panel products, have been summarized in the literature (Laufenberg 1988). A related aspect to this load duration effect is the time-dependent creep deformation. The literature on the rheological behavior of composite wood-based materials was reviewed earlier and augmented with new experimental data (Laufenberg 1987, 1989; McNatt and Laufenberg 1991; Palka 1989; Palka and Rovner 1990; Pu and others 1992a,b, 1994).

The rather small number of specimens tested from a single source in this study severely limits the quality of the statistical statements that can be made. However, the inferences gained from this preliminary research and the variety of the sampled materials were deemed useful in guiding further experimental work.

Throughout this paper, the term creep–rupture will be used to describe the phenomena of increasing deformation and loss of strength with time under constant loads, resulting in ultimate failure. Using the damage accumulation models for this creep–rupture phenomenon allows us to model the stochastic failure processes occurring during creep to rupture but does not allow us to relate the damage to actual creep behavior.

Objectives

The objectives for this baseline study of flexural creep and creep–rupture in wood-based panel products were to

- use standardized test methods to provide a consistent set of rheological properties for a wide range of wood-based structural panels,
- use analytical methods for describing and predicting panel behavior, and
- guide future research in panel rheology.

The study was conducted in three phases:

Phase I	Screening of commercial plywood, oriented strandboard (OSB), and waferboard products to select the appropriate specimens to be included in the two phases to follow
Phase II	Creep–rupture testing using three rates of ramp loading and three levels of constant loading under one environmental condition
Phase III	Creep testing using two levels of constant loading under three environmental conditions

This paper provides a brief overview of the experimental plan followed, test methods used, common elements of both short- and long-term databases collected, and conclusions reached in this joint U.S.–Canadian panel properties study.

Phase I: Screening of Panel Products

Goal

The goal for this phase of testing was to identify three plywood, three OSB, and three waferboard panel products that would encompass the range of creep bending properties available at the time. These nine products would then be used in the testing phases to follow. This was to assure that the final tests were performed considering the full performance range of commercially available panel products.

Materials

Nine plywood manufacturing mills, seven OSB mills, and seven waferboard mills were sampled for 15.6-mm- (5/8-in.-) thick material. The plywood and OSB panels had a span rating of 40/20, and standard quality control tests were conducted to assure their conformance with appropriate performance standards (APA 1982). The waferboard panels were tested for conformance to Grade P-1 as specified in Standard CAN-O188.2-M78 (CSA 1978). All 23 North American products sampled are listed in Table 1. These products represent all commercially produced 15.6-mm-thick panels manufactured for structural use in North America in 1985.

Table 1—Plywood, OSB, and waferboard materials (15.6 mm (5/8 in.) thick) sampled for Phase I static bending and creep evaluation

Mill	No. of plies or resin form	Region	Panels sampled
		Plywood	
A	5	West	3
B	5	West	2
C	4	West	3
D	4	South	3
E	4	South	3
F	5	West	3
G	4	South	3
H	4	South	3
I	4	South	1
		OSB	
J	Liquid	Great Lakes	2
K	Powder	Great Lakes	3
L	Liquid	Great Lakes	3
M	Powder	North East	3
N	Powder	South	3
O	Powder	Inland Empire	3
P	Powder	Rocky Mountain	3
		Waferboard	
W1	Powder	Quebec	5
W2	Powder	Quebec	5
W3	Powder	Quebec	5
W4	Powder	Ontario	5
W5	Powder	Ontario	5
W6	Powder	Ontario	5
W7	Powder	Ontario	5

Generally, each mill sample consisted of three panels (1.22 by 2.44 m). Bending test specimens were sized according to principles demonstrated by Bryan (1960) and Pierce and others (1977) to obtain span-to-depth ratios greater than 20. To include greater amounts of material in the most highly stressed bending region, third-point loading was used instead of the centerpoint loading. Six specimens (0.102 by 1.016 m) were cut from each panel from each of the supplying mills. Three of these specimens were cut with their long dimension parallel to the long panel dimension. Three were cut with their long dimension perpendicular to the long panel dimension. Within each group of three specimens, only the central specimen was used for the creep testing, while the two adjacent samples were used as controls in the short-term bending tests.

Test Methods

Short-Term Bending

After being conditioned at 20°C and 50% relative humidity (RH), the bending test specimens were loaded at their third-points across a 915-mm simply supported span. This provided a constant moment across the central 305 mm of the specimens. A cross-head speed of 0.33 mm/s was used. The testing principles and procedures for wood-based panel products were used to develop this procedure (ASTM D3043–76 and D1037–78) (ASTM 1984). Deflection at mid-span and load were continuously monitored and recorded through computer-interfaced transducers.

Creep Tests

The creep specimens were loaded to 25% of the average of the failing load of the side-matched controls, in an environmentally controlled 20°C, 50% RH room. This load level (1) was near the ratio of design load to average ultimate load for other wood products, (2) was deemed to be near the plausible design load for the various panel products (Laufenberg 1986), and (3) applied a wide range of actual loads, which reflected the variability of OSB, waferboard, and plywood materials. The span and third-point load specifications of the creep specimens were identical to those of the short-term bending tests. Application of the dead weight constant load was through a hydraulically controlled platform that brought each specimen from a no-load condition to the full-load condition in 10 s. The specimens' full span deflection was monitored for 56 days (8 weeks). This duration was

Table 2—Bending stiffness (MOE) and strength (MOR) of Phase I control specimens

	MOE[a] (GPa)		MOR[a] (MPa)	
Mill	Parallel	Transverse	Parallel	Transverse
		Plywood		
A	10.5 (8.1)	2.8 (8.5)	40.5 (21.7)	15.9 (34.9)
B	7.2 (6.0)	2.7 (8.7)	34.6 (23.4)	20.2 (10.2)
C	10.1 (26.0)	1.9 (21.2)	31.3 (45.6)	13.0 (25.5)
D	12.8 (11.7)	1.9 (18.5)	59.6 (13.8)	17.2 (26.1)
E	9.9 (10.8)	1.5 (12.1)	47.1 (25.7)	13.5 (17.6)
F	10.2 (24.0)	2.3 (29.8)	34.9 (33.7)	15.1 (48.1)
G	11.2 (13.8)	1.9 (13.8)	47.1 (25.7)	13.5 (17.6)
H	11.8 (12.5)	2.1 (30.1)	48.7 (21.4)	17.6 (30.6)
I	10.6 (18.4)	2.5 (5.3)	53.9 (16.9)	21.3 (28.3)
Average	10.5 (16.2)	2.2 (24.9)	44.2 (27.4)	16.4 (24.7)
		Oriented strandboard		
J	5.7 (5.5)	3.0 (11.9)	21.9 (12.8)	15.5 (11.4)
K	5.8 (6.9)	2.2 (6.9)	22.6 (12.4)	10.4 (9.0)
L	7.5 (3.9)	1.9 (9.1)	29.2 (17.5)	11.5 (8.7)
M	7.1 (8.7)	3.3 (8.2)	25.6 (18.0)	15.3 (18.3)
N	5.5 (7.6)	2.1 (13.7)	21.5 (5.3)	12.2 (14.5)
O	6.4 (6.9)	2.4 (8.8)	24.5 (11.3)	12.8 (17.4)
P	6.5 (6.4)	2.3 (8.6)	30.2 (14.7)	13.1 (10.4)
Average	6.4 (12.3)	2.5 (21.0)	25.1 (16.3)	13.0 (15.5)
		Waferboard		
W1	5.0 (8.0)	3.3 (7.0)	19.1 (14.9)	13.5 (18.1)
W2	3.9 (8.4)	2.9 (8.6)	15.1 (19.0)	11.2 (17.0)
W3	3.9 (5.5)	4.2 (9.5)	15.4 (6.6)	17.0 (9.5)
W4	4.9 (7.0)	5.1 (6.8)	20.7 (8.1)	20.7 (7.6)
W5	6.1 (3.1)	3.4 (7.8)	23.6 (4.3)	15.9 (8.2)
W6	4.8 (11.5)	3.8 (4.8)	19.9 (14.6)	17.1 (7.0)
W7	4.2 (10.5)	3.9 (6.7)	19.6 (10.3)	17.8 (6.4)
Average	4.7 (17.1)	3.8 (18.9)	19.1 (18.0)	16.2 (20.2)

[a]Coefficients of variation are given in parentheses.

considered to correspond to a typical snow load in service and was a reasonable length of time to measure creep deformation. Then, the load was removed via the hydraulic system, and measurement of creep recovery continued for an additional 21 days (3 weeks), for a total deflection–monitoring time of 11 weeks. Following these creep and creep-recovery tests, the residual bending strength of each specimen was determined using the short-term bending test procedure.

Results and Discussion

Control Specimens

Average bending stiffness (modulus of elasticity (MOE)) and strength (modulus of rupture (MOR)) values for the Phase I control specimens are shown in Table 2. Values are typically for six specimens (two specimens from each of three large panels). A summary of the Phase I testing (Table 3) provides insight to the wide range of panel bending properties encompassed in this testing. Note especially the range of MOE ratios with a plywood flexural stiffness ratio approaching 7 and a waferboard that was stiffer in the transverse than in the longitudinal direction (MOE parallel/transverse ratio of 0.9).

Residual Short-Term Strength

An analysis of variance on the side-matched control strengths and the residual short-term strengths of the creep specimens after unloading (Table 4) showed no statistically significant differences between the two sets of test results (95% confidence). Thus, no significant amount of mechanical property degradation was deemed to have occurred during the 8-week loading period. A major concern of the short-term testing was the matching of short-term strength properties by the use of side matching. It was clear from the data that the side matching of specimens yielded good matching of specimen properties across the entire range of materials tested.

Table 3—Ranges of property values from baseline testing of 23 panel products

Product	MOE (GPa)		MOR (MPa)		MOE ratio (parallel/ transverse)	Fractional creep[a]	
	Parallel	Transverse	Parallel	Transverse		Parallel	Transverse
Plywood	7.2–12.8	1.5–2.8	31–60	13–21	2.7–6.8	1.16–1.53	1.19–1.50
Oriented strandboard	5.5–7.5	1.9–3.3	22–30	10–16	1.9–4.0	1.41–1.94	1.54–1.79
Waferboard	3.9–6.1	2.9–5.1	15–24	11–21	0.9–1.8	1.37–1.65	1.57–1.69

[a] After being loaded for 8 weeks in 20°C/50% RH conditions at 25% of the average failure load for side-matched specimens.

Table 4—Residual stiffness (MOE) and strength (MOR) of Phase I creep specimens after unloading

Mill	MOE (GPa)		MOR (MPa)	
	Parallel	Transverse	Parallel	Transverse
		Plywood		
A	11.4	2.7	48.4	9.9
B	6.9	2.8	42.9	20.3
C	9.4	2.0	33.5	15.4
D	12.6	1.8	63.3	17.3
E	11.0	1.6	45.1	13.9
F	9.0	2.3	31.9	16.6
G	12.1	1.8	50.6	17.0
H	12.6	1.9	49.6	17.6
I	10.2	2.4	47.3	18.5
Average[a]	10.6 (18.4)	2.1 (23.4)	45.8 (28.6)	16.3 (26.4)
		Oriented strandboard		
J	5.9	3.1	20.3	14.2
K	6.0	2.4	22.1	10.7
L	8.1	2.1	30.9	12.6
M	7.4	3.5	25.8	16.1
N	6.1	2.2	23.1	13.7
O	7.0	2.5	25.1	13.1
P	7.3	3.3	27.4	14.5
Average[a]	6.8 (12.5)	2.7 (27.9)	25.0 (15.7)	13.6 (15.8)
		Waferboard		
W1	4.9	3.4	17.8	15.2
W2	3.9	2.9	15.7	11.7
W3	3.4	3.8	16.5	16.1
W4	5.0	4.9	19.3	19.9
W5	6.1	3.4	24.8	16.3
W6	3.8	3.7	17.0	18.4
W7	4.3	3.4	23.7	17.3
Average[a]	4.5 (20.5)	3.6 (17.1)	19.3 (18.8)	16.4 (15.8)

[a] Overall average coefficients of variation are given in parentheses.

Table 5—Results of Phase I creep tests in the 2.44- and 1.22-m direction of sample panels showing average parameters

	2.44-m direction				1.22-m direction			
Mill	Elastic deflection (mm)	Creep deflection (mm)	Permanent deflection (mm)	Fractional creep	Elastic deflection (mm)	Creep deflection (mm)	Permanent deflection (mm)	Fractional creep
				Plywood				
A	10.6	1.7	0.8	1.16	17.5	3.7	1.2	1.21
B	12.1	2.2	1.2	1.18	21.0	4.0	1.6	1.19
C	6.1	3.2	0.5	1.53	16.6	4.8	2.2	1.29
D	14.1	2.6	1.1	1.18	27.6	7.3	2.6	1.26
E	11.1	3.2	1.5	1.29	22.5	11.3	4.4	1.50
F	11.2	2.4	0.9	1.22	19.6	5.6	2.0	1.26
G	12.0	2.8	1.4	1.24	28.2	8.6	4.6	1.30
H	12.2	2.1	0.9	1.17	28.9	8.2	4.4	1.28
I	16.4	2.8	1.0	1.17	24.7	6.1	1.0	1.24
				Oriented strandboard				
J	9.3	3.8	1.6	1.41	13.9	7.5	3.5	1.54
K	9.8	7.8	4.4	1.79	12.5	8.9	5.4	1.72
L	8.6	4.2	1.9	1.49	16.1	10.3	5.0	1.64
M	9.8	6.5	4.5	1.66	12.4	7.3	3.7	1.59
N	7.0	6.6	2.0	1.94	14.8	11.3	6.3	1.77
O	8.6	6.9	3.7	1.80	13.4	10.6	6.1	1.79
P	10.3	5.2	2.0	1.56	16.5	11.0	9.6	1.67
				Waferboard				
W1	11.6	4.3	2.6	1.37	11.5	4.2	1.6	1.37
W2	10.8	5.2	2.7	1.49	10.6	5.2	2.8	1.49
W3	11.3	5.1	2.6	1.45	11.4	4.9	2.4	1.43
W4	11.4	5.7	2.6	1.46	11.4	4.6	2.3	1.40
W5	9.9	4.3	2.0	1.43	11.8	6.3	3.0	1.53
W6	12.5	6.1	2.8	1.49	11.9	5.5	2.6	1.46
W7	12.0	7.8	2.7	1.65	12.3	8.6	3.8	1.69

Creep Tests

The range of fractional creep test results is shown in Table 3. Table 5 shows creep test results for each sample mill's product. Definitions for these creep results follow:

Elastic deflection—Deflection of specimen immediately after the loading phase with negligible time (less than 10 s) for creep

Creep deflection—Obtained by subtracting elastic deflection from the deflection after 8 weeks under load

Permanent deflection—Deformation of specimen induced by the 8-week loading that was nonrecoverable after 3 weeks of recovery time without load

Fractional creep—Ratio of total 8-week deflection to elastic deflection

Modulus of elasticity was expected to be well correlated with creep deflection for similar materials (Laufenberg 1986). In Phase I, creep deflection was assessed across a range of material types, under a common stress level (25%). We found a moderate correlation between MOE and creep deflection and between MOE and total panel deflection at failure.

Material Selection for Phases II and III

The Phase I data allowed us to examine the creep behavior of these panel products prior to conducting the rest of the test program. Assuming a unique relationship between the short-term mechanical performance and the DOL characteristics, we were able to choose specific products for Phases II and III. The principal selection criterion was to achieve a range of static mechanical properties and creep performances.

Table 6—Panel products selected for Phases II and III of the project

Product	Mill	Creep (and other) attributes
Plywood	G	Low (high stiffness, 4-ply, southern)
	C	Medium (medium stiffness, 4-ply, western)
	B	High (low stiffness, 5-ply, western)
Oriented strandboard	L	Low (high stiffness, liquid resin)
	O	Medium (medium stiffness, powder resin)
	K	High (low stiffness, powder resin)
Waferboard	W4	Low (high stiffness, powder resin)
	W3	Medium (medium stiffness, powder resin)
	W2	High (low stiffness, powder resin)

Additional selection criteria were different for each material type. For plywood, it was desirable to test both a 4- and 5-ply western plywood and a 4-ply southern plywood. For the OSB, both the liquid and powder resins were represented. Waferboards were chosen to provide a range of creep performances from well-controlled manufacturing processes. The nine commercial panel products selected for detailed evaluation in Phases II and III, and their attributes, are summarized in Table 6.

Of the plywood products, mill C was the only 4-ply western product, so it was a necessary candidate. Mill C was not a consistently high or low performer; thus, it was designated as the medium creep product. The mill B product was chosen because of its low MOE. Because of inadequate production of mills D and H for obtaining the needed specimens for Phases II and III, the mill G product was chosen to represent the high stiffness product.

In selecting the appropriate OSB products for the next phases, we grouped the products into high, medium, and low stiffness categories. In the low stiffness group, products from mills J and K were equivalent; however, the mill K product was chosen because of a significantly higher creep deflection. High stiffness products were produced by mills L, M, and P, with mill L representing the lowest creep measurements of the three. A powder resin product (mill K) and a liquid resin product (mill L) were thus represented in our sampling. Selecting the mill O product as the medium performer was justified because its MOE and MOR nearly matched the OSB average values.

For the waferboards, mill samples with excessively large variability (coefficient of variation (CV) above 30%) or excessively small variability (CV below 7.5%), based on unit stress creep, were not considered typical; thus, these were excluded from consideration. Therefore, mills W2, W3, and W4 were identified as producers of typical and well-controlled high, medium, and low fractional creep waferboard panels, respectively.

Summary

The broad sampling of plywood, OSB, and waferboard provided an opportunity to look at a cross section of the structural panel industry. The objective of selecting products to be placed into the rest of the test program was accomplished. The repeatability of test results for selected short-term and long-term panel properties was verified for side-matched specimens. The new test data suggested that creep is only moderately, not highly, correlated with the initial product stiffness. The strategy adopted for selecting products relied on the premise that sampling could encompass both the wide range of stiffness values encountered in these panel products as well as the extremes of the creep measured in this phase of the study.

Phase II: Creep–Rupture Testing of Selected Panel Products

Goals

The goals for this phase of the study were to provide experimental creep and creep–rupture data under relatively high constant loads, to quantify damage accumulation model parameters, and to estimate conventional (deterministic) DOL factors for the plywood, OSB, and waferboard structural panels.

Materials

The three plywood, three OSB, and three waferboard products selected as a result of Phase I were independently collected from the manufacturers. The only stipulations placed on the sampling were that the products would be collected when the process was under control and over as short a time period as possible. These stipulations were intended to assure that the products would each have minimal within-product variability caused by changes in the processing factors.

Thirty (from United States) or twenty-five (from Canada) full-size (1.2- by 2.4-m) panels of each product were taken at random from the stack of panels received from the manufacturers. These were cut to produce six 0.3- by 1.0-m test specimens from each panel with the 1.0-m dimension parallel to the long panel dimension. A total of 1,530 test specimens were cut. This specimen size corresponds to the metric dimensions specified in the RILEM (1981) recommended international standard. One specimen from each panel was placed in each of the six types of tests (three ramp loading rates and three constant-load levels) discussed in the following section.

Table 7—Ramp-load test groups

Group	Target time to failure (s)	Number of specimens[a]
2	60	255
4	1,200	255
6	36,000	255

[a] Three materials each from three different suppliers (30 replicates for plywood and oriented strandboard, 25 replicates for waferboard).

Table 8—Constant-load test groups

Group	Median time to failure ($\times 10^6$ s)	Target stress levels (percentage of 1-min ramp test)			Number of specimens[a]
		Plywood	Oriented strandboard	Waferboard	
1	2 (3 weeks)	85	80	75	255
3	9 (3 months)	80	75	65	255
5	21 (8 months)	75	65	55	255

[a] Three materials each from three different suppliers (30 replicates for plywood and oriented strandboard, 25 replicates for waferboard).

Test Methods

Two test series were planned for Phase II. Specimens were either loaded using one of three ramp loading rates (Table 7) or were loaded to one of three constant-load levels (Table 8). These two types of tests provided the data needed to model failure time under load. All tests were conducted with specimens conditioned and maintained at 20°C and 50% RH, that is, under constant dry service condition.

The 0.3- by 1.0-m specimens were simply supported across a 0.9-m span. The ramp loads (Table 7) were applied at the one-third span points, to provide a 0.3- by 0.3-m uniform moment zone at the center of the specimen. Deflection was monitored across this 300-mm span relative to the loading rollers. The ramp load was applied according to a computer-controlled target rate using hydraulically actuated test equipment. Both the load and deflection of the specimen were continuously monitored during the test.

The other half of the creep–rupture specimens were subjected to a constant rate of loading up to preselected levels (Table 8) of constant loads. Then, each specimen remained constant loaded (Fig. 1a) until it failed or was unloaded manually after 8 months (2.1×10^7 s) of load duration.

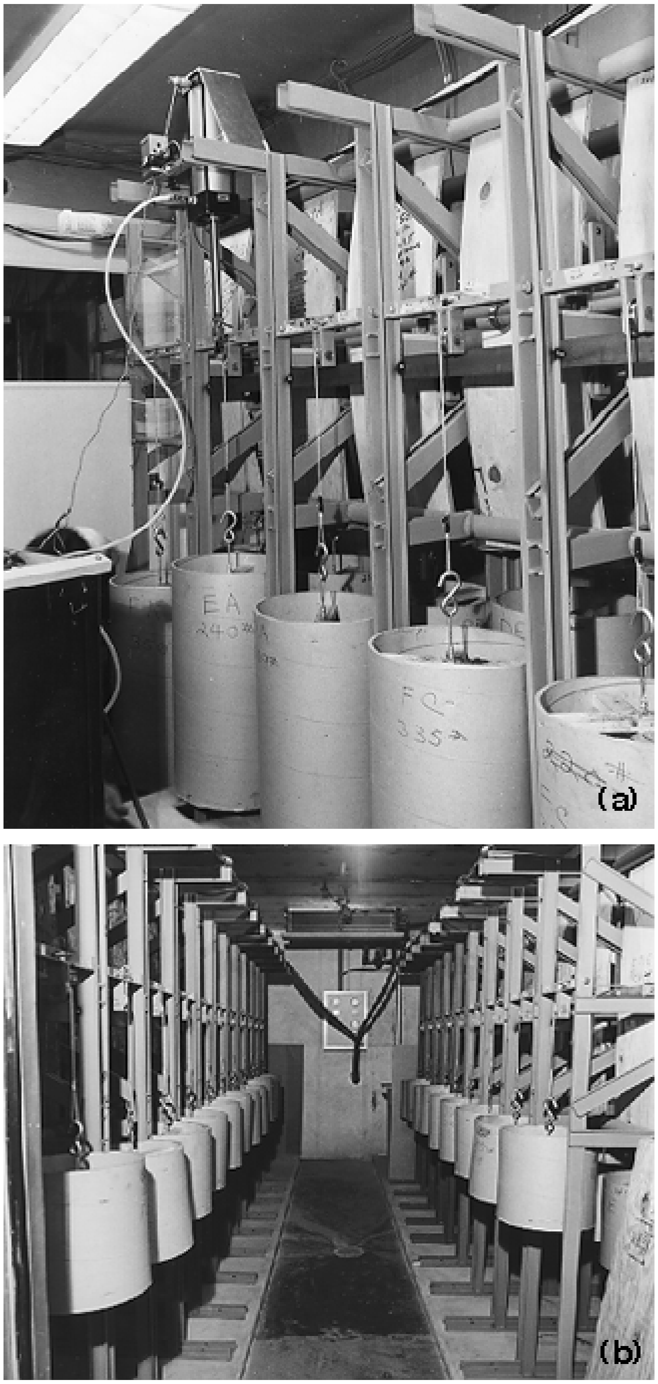

Figure 1—Test setup for (a) creep–rupture (Phase II) and (b) creep (Phase III) tests.

The stress levels were selected based on results of other investigators (Hoyle and Adams 1975, Kufner 1970, Bryan 1960) to produce comparable failure times for each material. The OSB and waferboard panels were expected to be more sensitive to DOL effects than the plywood, and the population variability of their mechanical properties is lower than that of the plywoods; thus, their constant stress levels were reduced, as shown in Table 8. These load levels were expected to produce failure of 80% of the specimens placed under long-term loads.

Each OSB and plywood specimen was loaded with a dead weight constant load, which took into account the friction losses in the loading apparatus. No friction load adjustments were attempted for the waferboard specimens. The dead weight was gradually lowered by a pneumatic ram to load the specimen. Specimen loading configuration was the same here as that used in the ramp-load tests.

Analysis Methods

The stress level and time to failure data from both ramp-loaded to failure and constant-loaded to failure tests were analyzed using the damage accumulation (DA) model (Gerhards and Link 1983, 1987). We provide some additional background on the development and use of the DA model in the Appendix. The essence of the model is

$$\mathrm{SL} = \frac{P_c}{P_0} = \frac{1}{P_0}\left(\frac{b'}{c} - \ln T\right)\exp\frac{wR}{b'} \quad \text{for constant load} \qquad (1)$$

and

$$\mathrm{SL} = \frac{P_r}{P_0} = \frac{1}{P_0}\left(\frac{b'}{c} + \ln b'k\right)\exp\frac{wR}{b'} \quad \text{for ramp load} \qquad (2)$$

where k is ramp loading rate; b and c are model parameters; T is time to failure (s); SL is stress level; P_c is constant load applied; P_r is maximum ramp load applied; P_0 is median strength; w is measure of variability; and R is standard normal random variable.

This DA model was used to provide parameters c, b' and w for the DOL effect using both the ramp-load data and the constant-load data, as indicated in the Appendix. Additionally, the constant-loaded time to failure data were analyzed using a simple exponential model (Wood 1951, Bryan 1960, Laufenberg 1988):

$$\mathrm{SL} = P_c / P_0 = A + B \ln T \qquad (3)$$

where A is the y intercept for SL compared with time ($\ln T = 0$), and B is the slope of the regression line.

The stress level used in these analyses refers to the estimated fraction or percentage of the failing load over the matched reference strength for the individual specimens. An assumption was made that the lowest strength specimen always fails first in all ramp- and constant-load tests. Therefore, all ramp-load tests were ranked by failure strength and constant-load tests were ranked by time to failure. This is usually termed as the equal-rank assumption and was used for matching individual specimens from the short-term control group to those in the long-term treated groups.

Results and Discussion

Ramp-Load Tests

Results of the ramp-load tests are summarized in Table 9. We used the 1-min test (the fastest ramp rate) as the control reference. Stiffness and strength values of panels loaded at the median ramp rate averaged 88% to 102% of the controls. At the slowest ramp load rate, MOE and MOR values averaged 84% to 98% of the controls. A slight decrease in average strength was observed with increasing load durations for all three structural panels (Figs. 2 to 4).

Perhaps the most striking feature of the ramp-loaded time to failure testing is the high variability in strength and time to failure of the plywood materials. Strength variability is a function of specimen size, more so for plywood than for the other materials. Although each plywood mill represents a different population, all three products are shown together. Note that the range of results is quite unlike that of the OSB or waferboard materials. The wide range of population performance for plywood presented a challenge as we attempted to model 10-year performance under constant loads from data collected under ramp loading for ~10 h.

Linear regressions (and corresponding 95% confidence intervals) were fit to the ramp-load data of Figures 2 to 4. Each material demonstrates a reduction in population strength with increasing ramp-loaded time to failure. However, the regression fit to these data does not allow us to extrapolate to constant loading for extended periods.

Constant-Load Tests

Load levels were highest for plywood and lowest for waferboard (Table 8). Time to failure during the constant-load tests included failures on uploading (<60 s) and extended to nearly 40 weeks. A total of 554 specimens failed during the constant-load testing including 64 plywood specimens that did not survive uploading. These uploading failure data were used in the DA model estimates of the parameters c, b', and w. None of the OSB or waferboard specimens failed during uploading. Also, 207 specimens (83 waferboard, 73 OSB, and 51 plywood) survived the constant-load testing. Specimens had to be removed from the testing machines after 6 months of load duration to allow other tests to be completed in a timely manner. Nonetheless, the data from those unfailed specimens were still used in the DA modeling because they were equated with the strongest portion of the population.

Results of the constant-load tests are shown in Figures 5 to 7 with a regression fit of the exponential model to the data points. The data shown include only those specimens that failed after reaching the assigned constant-load level. Each specimen's failure stress level was determined through matching the population of failures obtained from 1-min ramp testing. Consistent with the ramp-load data, the

Table 9—Results of Phase II ramp-load tests[a]

Mill	Loading rate (N/s)	Time to failure (s)	Maximum load (kN)	Modulus of elasticity (GPa)	Modulus of rupture (MPa)
Target load rate: 60 s to failure					
Plywood					
G	56.39	57 (34.2)	3.24 (34.2)	11.1 (28.4)	45.4 (34.9)
C[b]	39.62	57 (38.0)	2.47 (36.5)	11.8 (19.7)	30.3 (38.4)
B	45.21	82 (18.7)	3.74 (18.9)	11.1 (11.4)	47.8 (19.1)
Oriented strandboard					
L	38.34	65 (11.9)	2.50 (11.8)	9.9 (9.6)	30.1 (11.3)
O	34.62	71 (12.9)	2.42 (9.0)	8.4 (9.5)	28.6 (8.5)
K	35.12	54 (19.0)	1.80 (8.4)	7.0 (9.2)	19.7 (8.7)
Waferboard[c]					
W4	24.22	71 (9.4)	1.71 (10.0)	5.0 (9.1)	20.6 (10.9)
W3	24.22	58 (9.7)	1.41 (9.5)	3.7 (7.1)	16.0 (9.4)
W2	24.12	64 (16.3)	1.56 (17.4)	4.1 (9.4)	17.8 (13.8)
Target load rate: 1,200 s to failure					
Plywood					
G	2.70	1,210 (28.1)	3.34 (26.2)	10.7 (31.6)	46.3 (27.3)
C	2.11	1,030 (34.4)	2.22 (33.3)	10.6 (28.3)	29.3 (33.4)
B	3.12	1,120 (17.6)	3.55 (17.2)	9.8 (11.6)	45.0 (17.5)
Oriented strandboard					
L	2.09	1,140 (9.7)	2.41 (9.5)	9.5 (6.5)	29.1 (9.3)
O	2.05	1,090 (7.4)	2.27 (7.6)	8.0 (6.7)	26.4 (8.2)
K[d]	1.50	1,210 (11.0)	1.85 (11.0)	7.3 (14.5)	20.1 (10.8)
Waferboard[c]					
W4	1.25	1,330 (9.5)	1.66 (9.5)	5.1 (9.6)	20.1 (9.3)
W3	1.25	1,160 (9.0)	1.44 (9.2)	3.8 (6.9)	16.4 (9.5)
W2	1.25	1,140 (14.8)	1.42 (14.9)	4.2 (10.0)	16.8 (10.8)
Target load rate: 36,000 s to failure					
Plywood					
G[c]	0.10	28,500 (28.0)	2.82 (29.1)	10.2 (31.4)	39.1 (29.6)
C[e]	0.08	26,100 (34.4)	2.01 (30.8)	11.0 (20.1)	27.0 (31.2)
B	0.12	30,300 (16.0)	3.35 (15.6)	10.1 (12.7)	42.6 (15.8)
Oriented strandboard					
L[d]	0.07	29,800 (12.0)	2.18 (9.9)	8.7 (7.9)	25.8 (9.4)
O	0.07	28,800 (9.0)	2.09(8.5)	7.1 (7.1)	24.0 (7.8)
K	0.06	32,000 (12.6)	1.74 (11.9)	6.9 (11.5)	18.5 (9.7)
Waferboard[c]					
W4	0.04	36,300 (9.7)	1.48 (9.7)	4.9 (7.6)	18.0 (8.8)
W3	0.04	31,400 (8.9)	1.28 (8.9)	3.7 (6.9)	14.6 (9.6)
W2	0.04	30,800 (17.4)	1.26 (17.5)	3.9 (11.7)	14.5 (15.1)

[a] Values are averages from 30 specimens except as otherwise indicated. Coefficients of variation are shown in parentheses.

[b] Modulus of elasticity and time to failure are average of 11 specimens due to loss of electronic data for the other 19 tests.

[c] Average of 25 specimens.

[d] Average of 29 specimens.

[e] Average of 27 specimens.

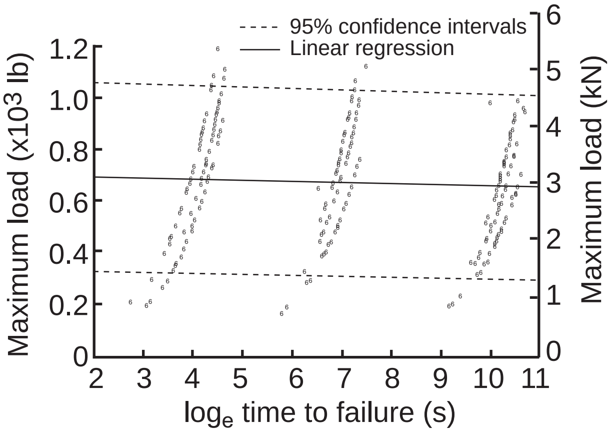

Figure 2—Maximum load plotted with natural logarithm of failure time for ramp-loaded plywood specimens.

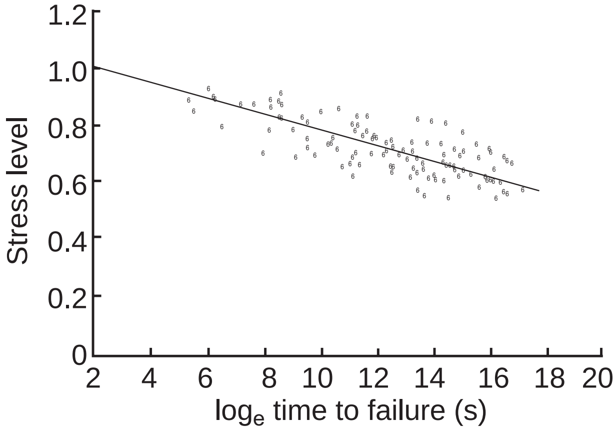

Figure 5—Stress level plotted with natural logarithm of failure time for constant-loaded plywood specimens.

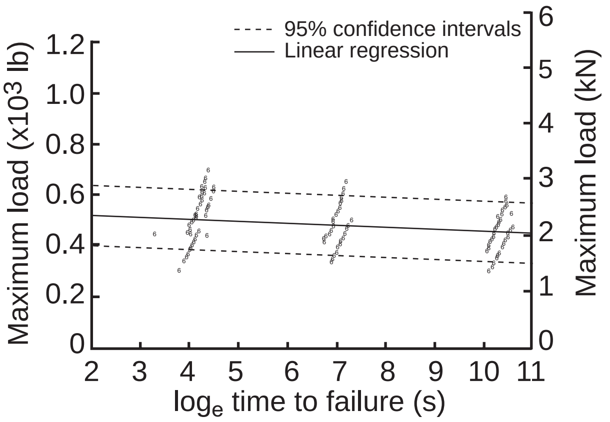

Figure 3—Maximum load plotted with natural logarithm of failure time for ramp-loaded oriented strandboard specimens.

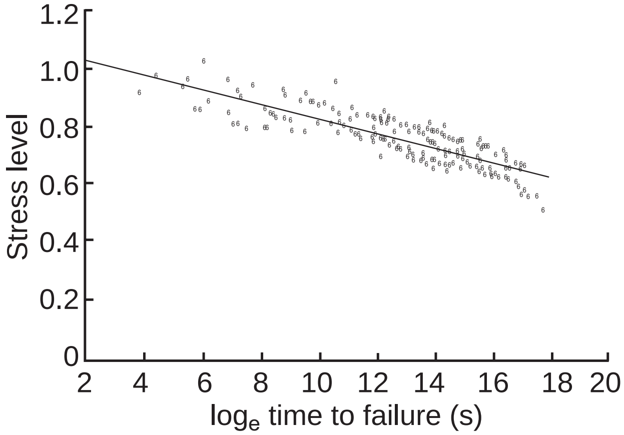

Figure 6—Stress level plotted with natural logarithm of failure time for constant-loaded oriented strandboard specimens.

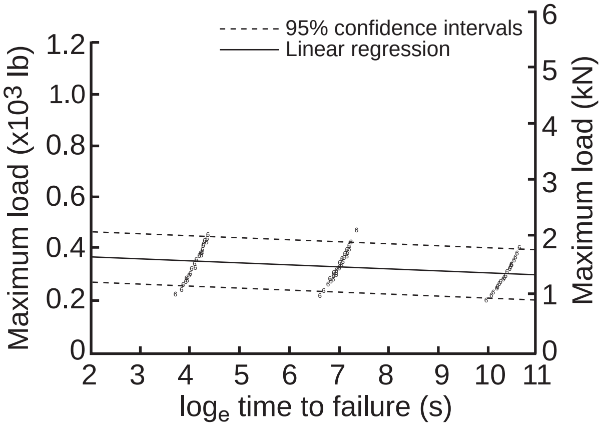

Figure 4— Maximum load plotted with natural logarithm of failure time for ramp-loaded waferboard specimens.

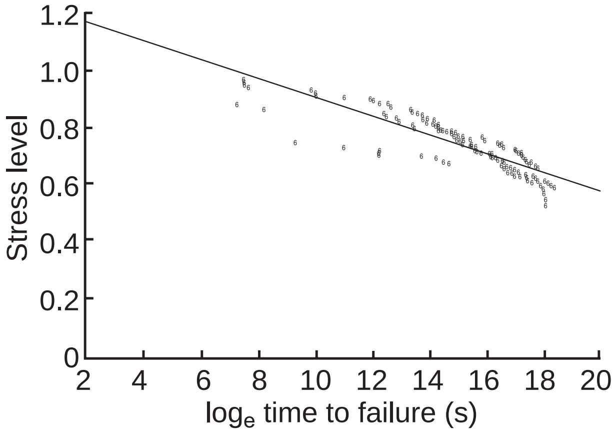

Figure 7—Stress level plotted with natural logarithm of failure time for constant-loaded waferboard specimens.

Table 10—Estimates and standard errors of parameters in Gerhards's damage accumulation model from the ramp-load data

	Parameter estimates[a]		
Mill	*c*	*b′*	*w*
	Plywood		
G[b]	0.1078 —	— —	0.5166 —
C	0.1298 (0.004362)	4.537 (2.011)	0.3961 (0.03502)
B[b]	0.09968 —	— —	0.5817 —
	Oriented strandboard		
L	0.1152 (0.001018)	5.101 (0.7610)	0.1095 (0.009152)
O	0.1204 (0.0008372)	4.976 (0.5365)	0.08717 (0.007142)
K[b]	0.1513 (0.001443)	— —	0.1070 (0.009271)
	Waferboard		
W4	0.002560 (0.00004280)	0.12220 (0.01768)	0.09977 (0.009294)
W3	0.003104 (0.00005104)	0.2119 (0.04822)	0.09340 (0.009768)
W2	0.002844 (0.0008536)	0.09756 (0.01727)	0.1794 (0.01665)

[a] For panel strength in pounds and rate of loading in pounds per second (1lb = 4.45 N). Standard errors are shown in parentheses.

[b] For mills G, B, and K, not all parameter estimates could be generated.

population variability within the three plywood mills is elevated (Fig. 5). Within the OSB and waferboard data (Figs. 6 and 7), the lower levels of variability, as seen in the short-term testing, are seen in the constant-load time to failure data.

Damage Accumulation Model

Estimates for the parameters *c*, *b′*, and *w* in the DA model from the ramp-load data are given in Table 10 for individual mills. The corresponding conventional DOL factors are listed in Table 11. Estimates for the parameters *c*, *b′*, and *w* in the DA model from the constant-load data are given in Table 12. The corresponding conventional DOL factors are presented in Table 13. The procedure for calculating conventional DOL factors from the Gerhards–Link DA model is given in the Appendix.

Inspection of Tables 11 and 13 reveals that DA is more severe under constant than under ramp loads, as expected. Consequently, specimens under constant load showed a higher strength loss and exhibited lower DOL factors than specimens subjected to ramp loads. The DOL factors calculated from the DA model parameters from constant-load tests for structural panels were lower than the DOL factors recommended for lumber in the National Design Specification (NDS) (AFPA 1997). However, the NDS DOL factors were derived from an exponential model and were referenced to 7.5 min (Wood 1951).

A significant problem in use of the DA model using ramp-load data was the model's inability to generate *b′* parameter estimates and most standard errors for materials from three mills: G, B, and K. Thus, the model is unable to establish a DOL effect. In fact, three of these materials showed a higher average strength with the 20-min testing than with the 1-min test. In addition, the model was not able to generate a standard error for *b′* or *w* when analyzing the constant-load data.

Table 11—Conventional duration of load factors[a] for ramp loading calculated from Gerhards's damage accumulation model

	Fraction of 5-min strength	
Mill	2 months	10 years
	Plywood	
G	1 (0,1)	1 (0,1)
C	0.67 (0.32,1)	0.53 (0.04,1)
B	1 (0,1)	1 (0,1)
Average	0.89	0.84
	Oriented strandboard	
L	0.75 (0.66,0.83)	0.64 (0.52,0.76)
O	0.73 (0.66,0.79)	0.61 (0.52,0.70)
K	1 (0,1)	1 (0,1)
Average	0.83	0.75
	Waferboard	
W4	0.77 (0.67,0.82)	0.67 (0.53,0.74)
W3	0.78 (0.71,0.89)	0.72 (0.58,0.85)
W2	0.66 (0.46,0.74)	0.52 (0.23,0.63)
Average	0.74	0.64
NDS[b]	0.71	0.62

[a] Ninety-five percent confidence intervals are shown in parentheses.

[b] National Design Specification for Wood Construction (AFPA 1997).

Table 12—Estimates and standard errors of parameters in the Gerhards's damage accumulation model for constant-load data

Mill	Parameter estimates[a]		
	c	b'	w
	Plywood		
G[b]	0.001017 (0.0006637)	0.02285 —	0.7941 —
C	0.002068 (0.0001961)	0.1101 (0.06992)	0.2430 (0.1516)
B	0.001221 (0.0001018)	0.07079 (0.02772)	0.1710 (0.06158)
	Oriented strandboard		
L	0.001580 (0.00007717)	0.06271 (0.008727)	0.09352 (0.01349)
O	0.001748 (0.00006012)	0.06809 (0.007122)	0.1015 (0.01250)
K	0.001940 (0.0001418)	0.06908 (0.01179)	0.1250 (0.02190)
	Waferboard		
W4	0.002063 (0.0001028)	0.06681 (0.006546)	0.09384 (0.01219)
W3	0.001494 (0.0001609)	0.04059 (0.006896)	0.1384 (0.02218)
W2	0.001967 (0.0002655)	0.05408 (0.01305)	0.2732 (0.05612)

[a] For panel strength in pounds (1lb = 4.45 N). Standard errors are shown in parentheses.
[b] For mill G, standard errors could not be estimated.

Exponential Model

Regression equations were developed for the products from the three individual plywood, OSB, and waferboard mills, based on the exponential stress level model (Eq. (3)). The resulting values for intercept A and slope B are shown in Table 14. Note that the magnitude of stress level is inversely related to load duration. Thus, a reference strength based on the 5-min test will yield higher DOL factors than one based on the 1-min test.

Table 15 shows the corresponding conventional DOL factors, as a fraction of the 5-min reference strength for each mill. For example, the 2-month DOL factor for OSB from mill L (0.68) is calculated by

$$\begin{aligned} \text{DOL} &= (A + B \ln T)/(A + B \ln T \text{ reference}) \\ &= \text{SL (2 month)/SL (5 min)} \\ &= [1.20 - 0.033(15.461)]/[1.201 - 0.033(5.704)] \\ &= 0.68 \end{aligned} \qquad (4)$$

Table 13—Conventional duration of load factors[a] for constant loading calculated from Gerhards's damage accumulation model

Mill	Fraction of 5-min strength at	
	2 months	10 years
	Plywood	
G	0.42 (0,1)	0.17 (0,1)
C	0.79 (0.55,1)	0.71 (0.36,1)
B	0.81 (0.69,0.94)	0.73 (0.56,0.91)
Average	0.67	0.54
	Oriented strandboard	
L	0.71 (0.65,0.77)	0.59 (0.51,0.67)
O	0.71 (0.66,0.75)	0.58 (0.51,0.65)
K	0.67 (0.60,0.75)	0.54 (0.43,0.64)
Average	0.70	0.57
	Waferboard	
W4	0.63 (0.58,0.67)	0.48 (0.40,0.53)
W3	0.55 (0.43,0.60)	0.35 (0.20,0.43)
W2	0.55 (0.30,0.63)	0.36 (0.01,0.47)
Average	0.58	0.40
NDS[b] (7.5-min. reference)	0.71	0.62

[a] From Equation (A14) in the Appendix. Ninety-five percent confidence intervals are shown in parentheses.
[b] National Design Specification for Wood Construction (AFPA 1997).

The conventional DOL factors calculated from the combination of data from all three mills in the exponential model would readily surpass the 2-month NDS recommendations (for lumber). The NDS factors were based on a 7.5-min static strength used for reference (Wood 1951).

Calculation of the 10-year DOL factors (Table 15) indicates that OSB has 5% more strength, waferboard is nearly equal (<1% difference), and plywood has 4% less of its 7.5-min strength after 10 years of loading than predicted by NDS. With each mill's (uncombined) data and the reference

Table 14—Intercepts and slopes for regression lines through constant-load data over natural logarithm of time using the exponential model (Eq. (3)) for estimating stress levels

Mill	Inter-cept	Slope	r^2	Reference strength
		Plywood		
G	1.094	–0.03	0.80	5-min test
C	0.838	–0.02	0.76	5-min test
B	1.105	–0.03	0.81	5-min test
Combined	1.081	–0.03	0.50	1-min test
		Oriented strandboard		
L	1.201	–0.03	0.88	5-min test
O	1.028	–0.03	0.92	5-min test
K	1.209	–0.03	0.88	5-min test
Combined	1.073	–0.03	0.70	1-min test
		Waferboard		
W4	1.819	–0.067	0.81	5-min test
W3	1.899	–0.066	0.57	5-min test
W2	1.129	–0.030	0.54	5-min test
Combined	1.222	–0.032	0.75	1-min test

Table 15—Conventional duration of load factors for constant loading, based on the exponential model

	Fraction of 5-min strength	
Mill	2 months	10 years
	Plywood	
G	0.66	0.51
C	0.79	0.70
B	0.72	0.61
Combined		
1-min strength	0.68	0.54
7.5-min strength	0.73	0.58
	Oriented strandboard	
L	0.68	0.55
O	0.72	0.61
K	0.70	0.57
Combined		
1-min strength	0.74	0.63
7.5-min strength	0.79	0.67
	Waferboard	
W4	0.55	0.36
W3	0.58	0.40
W2	0.69	0.55
Combined		
1-min strength	0.70	0.57
7.5-min strength	0.75	0.61
NDS[a] (7.5-min. reference)	0.71	0.62

[a]National Design Specification for Wood Construction (AFPA 1997).

strength of 5 min, only one product (plywood from mill C) exceeds the NDS DOL factor for lumber at 10 years.

Summary

For a variety of reasons, the outcome of the creep–rupture testing and analysis in Phase II is not certain. A summary of the combined data for each material is shown in Table 16. The fact that these data were combined (across three mills to create a database of up to 300 specimens for each material type) tended to mask specific behaviors with individual mills. Comparison of the DOL factors predicted for 2 months and for 10 years with the NDS DOL factors supports the statement that composite panel products do not behave significantly different from the clear wood tested by Wood (1951). Without further testing, none of the data from sampled materials for Phase II would justify a change from the NDS DOL factor.

Among the different evaluation techniques used in this phase, the DA model using constant-load data provided predictions incorporating the data from failures on uploading and the specimens that survived the loading period. The ramp-load data and analysis show that the material variability (especially plywood) could not be accommodated with the number of specimens we tested. The exponential model provided parameters that appear appropriate; however, the model has no mechanism for inclusion of specimens that survive or specimens that fail on uploading. Moreover, the model appears to be unduly sensitive to the reference strength chosen if the sample has few failures in the first few days of testing.

Phase III: Creep Testing of Selected Panel Products

In this phase of the study, we tested the flexural creep deflection of panels from three plywood, OSB, and waferboard mills under the influence of three environmental conditions and two constant-load levels.

Table 16—Summary of duration of load factors for creep–rupture models

	2 months			10 years		
Model	Plywood	Oriented strandboard	Waferboard	Plywood	Oriented strandboard	Waferboard
Damage accumulation						
Ramp	0.89	0.83	0.74	0.84	0.75	0.64
Constant	0.67	0.70	0.58	0.54	0.57	0.40
Exponential	0.73	0.79	0.75	0.58	0.67	0.61
NDS[a]	0.71	0.71	0.71	0.62	0.62	0.62

[a] National Design Specification for Wood Construction (AFPA 1997).

Materials and Testing

These test panels were obtained from the same sample of material that was used in the Phase II creep–rupture testing. An identical loading pattern (third-point bending) and large specimen size (0.3 by 1.0 m) provided results that were comparable between the two test phases (Fig. 1). Creep tests were performed in three environmental conditions: constant 50% RH, constant 85% RH, and cyclic 50% to 85% RH (~4.7 days per cycle) under constant nominal 20°C temperature. These tests were continued for six months. Waferboards were subjected to cyclic changes every 4 days and extended to 5 days on weekends.

Two load levels were used in all the environments to simulate realistic service load conditions. These loads were 15% and 30% of the ultimate strength measured in Phase II with a ramp-loaded test to failure in ~1 min. As with the Phase II tests, the creep loads were initially ramp applied up to the specified constant-load levels, at a rate that, if continued, would produce failure in a 1-min test.

Creep performance has been traditionally regarded as a noncritical or serviceability aspect of structural design, and there has been little need to know the full statistical distribution of this characteristic (Laufenberg 1986). For this reason, testing was limited to three specimens. A total of 162 large panel specimens were continuously monitored during creep testing, and the data were collected automatically. There were no failures of these specimens during the 6-month creep testing.

Waferboard creep deflection values (Tables 17 and 18) were adjusted to account for friction within the load apparatus, predicted elastic responses, and major breakdowns in the environmental conditioning equipment. More information on how these adjustments were made can be found in detailed Forintek reports (Palka and Rovner 1990).

Analysis

A number of empirical and visco-elastic models were examined to characterize the time-dependent behavior of all the specimens tested. Each modeling method had its advantages and limitations. As expected, there were better correlations between measured and predicted values when additional parameters were introduced in the modeling. Overall, the four-parameter creep model reported earlier by Pierce and others (1977) provided the best fit for the measured medium-term deflections or strains, ignoring the tertiary stage:

$$D(t) = [B_0 + B_1(1 - e^{-B_2 t}) + B_3 t]P_0 \approx P_0(1 + At^{B(t)}) \qquad (5)$$

or

$$e(t) = [A_0 + A_1(1 - e^{-A_2 t}) + A_3 t]s \approx s_0(1 + Ct^{D(t)}) \qquad (6)$$

However, the simplicity of the two-parameter power function creep models, with $B(t) = B$ and $D(t) = D$, was highly appealing for practical purposes. In these equations, $D(t)$ and $e(t)$ are creep deflection or strain, P_0 and s_0 are constant load or stress, and B_i, A_i, A, C, $B(t)$, and $D(t)$ are fitted creep parameters.

However, these parameters were not independent of each other and the service loads and environmental conditions. Thus, each specimen displayed its own unique parameters, with extremely high variability within each panel type.

Results and Discussion

To illustrate the form of the data recorded during the tests, Figure 8 shows a typical creep curve for an OSB sample in the cyclic environment. At 2 days, the 50% RH was switched to 85% RH resulting in a doubling of total deflection by the end of 4 days when the conditions in the room returned to 50% for the remainder of the week. When conditions were switched back to 50% RH, the specimen literally pulled the dead weight up to reduce deflection. The average rebound for the specimen was 0.15 mm. To assess the effect of

Table 17—Average deflection of structural panels loaded at constant stress levels and at 20°C[a]

	50% RH			85% RH			Cyclic 50% to 85% RH		
Mill	Initial (mm)	6 month (mm)	Creep (mm)	Initial (mm)	6 month (mm)	Creep (mm)	Initial (mm)	6 month (mm)	Creep (mm)
15% stress level									
Plywood									
G	0.43	0.61	0.18	0.56	1.02	0.46	0.51	0.89	0.38
C	0.33	0.53	0.20	0.66	1.32	0.66	0.36	0.76	0.41
B	0.69	0.91	0.23	0.66	1.22	0.56	0.66	1.27	0.61
Oriented strandboard									
L	0.43	0.79	0.36	0.53	1.93	1.40	0.43	1.57	1.14
O	0.51	0.89	0.38	0.30	1.91	1.60	0.51	1.83	1.32
K	0.38	0.74	0.36	0.25	1.91	1.65	0.28	1.83	1.55
Waferboard (adjusted)[b]									
W4	0.86	1.40	0.53	1.07	2.29	1.22	0.91	2.69	1.78
W3	0.91	1.40	0.48	1.22	3.15	1.93	1.04	2.59	1.55
W2	1.04	1.57	0.53	1.24	3.35	2.11	1.32	4.06	2.74
30% stress level									
Plywood									
G	1.12	1.37	0.25	1.14	2.06	0.91	1.17	3.25	2.08
C	0.81	1.12	0.30	0.91	1.75	0.84	0.91	1.57	0.66
B	1.55	1.88	0.33	1.42	2.87	1.45	1.75	3.40	1.65
Oriented strandboard									
L	1.09	1.60	0.51	1.19	5.26	4.06	1.19	4.85	3.66
O	1.17	1.83	0.66	1.09	4.29	3.20	1.04	4.75	3.71
K	0.89	1.37	0.48	0.66	3.78	3.12	0.86	4.39	3.53
Waferboard (adjusted)[b]									
W4	1.70	2.82	1.12	2.08	5.92	3.84	1.75	5.64	3.89
W3	1.75	2.57	0.81	2.18	6.12	3.94	1.83	5.97	4.14
W2	2.44	3.71	1.27	2.82	8.79	5.97	2.67	8.99	6.32

[a] Creep = total (6-month) deflection – initial (1-min) deflection.
[b] Adjustments to creep deflections were made to account for friction in the loading devices, calculated elastic responses, and environmental variability in test chambers.

changing cycle length, the average time at each condition was changed from 2.3 to 3.5 days for the last month of the test. Though noticeable, due to the time between rebounds, the deflection trend appears to be relatively unchanged.

Tables 17 and 18 summarize the average initial (1-min elastic) and final (6-month) deflections for the plywood, OSB, and waferboard panels at two stress levels and three humidity conditions, all at 20°C. Generally, creep was found to increase from plywood to OSB and from OSB to waferboard. For all three products, total deflections after 6 months in the constant 85% RH and in the cyclic 50% to 85% RH environments were not very different. Total deflection of waferboard and OSB in these two environments averaged more than 200% that in the constant 50% RH condition, while the plywood was consistently less than 200%.

Naturally, actual deflections (Table 17) were proportionately different for the two low load levels (15% and 30%). However, the corresponding fractional creep values (Table 18) (total 6-month deflection divided by initial 1-min elastic

Table 18—Average fractional creep (FC)[a] and baseline fractional creep (FC_b)[b] of structural panels after six months under low constant loads[c] and at 20°C

	50% RH		85% RH		Cyclic 50% to 85% RH	
Mill	FC	FC_b	FC	FC_b	FC	FC_b
			Plywood			
G	1.3	1.0	1.8	1.6	2.3	2.0
C	1.5	0.9	2.0	1.7	1.9	1.2
B	1.3	1.5	1.9	2.1	1.9	2.3
Average	1.4	1.1	1.9	1.8	2.0	1.8
			Oriented strandboard			
L	1.6	1.3	4.0	3.6	3.9	3.2
O	1.7	1.4	5.1	3.2	4.1	3.3
K	1.7	1.1	6.6	3.0	5.8	3.2
Average	1.7	1.3	5.2	3.3	4.6	3.2
			Waferboard (adjusted)[d]			
W4	1.6	2.2	2.5	4.1	3.1	4.3
W3	1.5	2.1	2.7	4.9	2.9	4.4
W2	1.5	2.7	2.9	6.1	3.2	6.7
Average	1.5	2.3	2.7	5.0	3.1	5.1

[a] FC = total (6-month) deflection/initial (1-min) deflection.

[b] FC_b = total (6-month) deflection/baseline (1.27 mm for 30% loading and 0.635 mm for 15% loading level).

[c] Low constant loads are 15% and 30% loads; FC and FC_b are averaged.

[d] Adjustments to creep deflections were made to account for friction in the loading devices, calculated elastic responses, and environmental variability in test chambers.

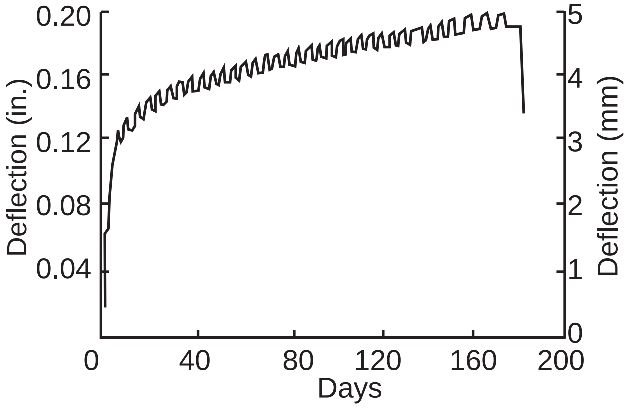

Figure 8—Creep deflection of a median oriented strandboard specimen in cyclic 50% to 85% relative humidity environment.

deflection) were not significantly different. Therefore, test data for the two load levels were combined. Table 17 shows also that initial (elastic) deflections were nearly the same in all three environments. This means that values for fractional creep (total deflection/initial deflection), summarized in Table 18, can be readily compared between different environments. Fractional creep substantially increased under environments of increasing severity (Table 18).

At 50% RH, fractional creep values at 6 months averaged 1.4 for the plywoods, 1.7 for OSB, and 1.5 for waferboards. For the 85% RH, fractional creep values averaged 1.9 for the plywood specimens, 5.2 for OSB, and 2.7 for waferboards. Fractional creep under cyclic RH conditions averaged ~2.0 for plywood, 4.6 for OSB, and 3.1 for waferboard.

Use of the fractional creep ratio provides an indication of change relative to the elastic or initial deflection condition. It does not provide a means for comparing deflections between various materials. In terms of the performance expectations for these panels in service, we advocate a comparison of all materials against a common baseline value of deflection. That baseline deflection value should relate to accepted limits such as the span length divided by 240 (Laufenberg 1986). To facilitate this performance-based comparison, we chose a baseline deflection value of span divided by 240. For the 300-mm uniform moment span over which the creep measurements were made, the baseline deflection value selected was 1.27 mm for the 30% stress level (and proportionately, 0.635 mm for the 15% stress level).

The original design of these experiments was to provide indications of creep behavior at low stress levels similar to those that might be encountered in service. We believe that the load levels used were appropriate for simulating such designed service situations. However, the high and cyclic RH environments are considered atypical and represent extreme conditions for panel service.

Summary

The 6-month creep data collected at 50% RH support the use of a doubling of the elastic deflection to account for creep effects under dry service conditions, as suggested in current specifications for panel products (O’Halloran and Elias 1988). These data also indicate that the application of loads for periods longer than 6 months, and loading in environmental conditions with high or cyclic humidity, would necessitate the use of larger creep deflection adjustments. Evidently, more information is needed to provide realistic measures of creep under uncontrolled environmental service conditions. Additional waferboard tests undertaken at Forintek Canada Corp. in heated and unheated warehouse environments already provided some information on the behavior of composite panel products in simulated service conditions (Palka and Rovner 1990). Discussion of those results, however, is beyond the scope of this report.

Conclusions

We have developed a broad database for creep–rupture performance of structural panel products. With test techniques adopted from large panel test standards, we obtained time to failure and creep data for realistic design loading and for a wide range of environmental conditions.

Creep and creep–rupture for panel products were found to be highly sensitive to both constant-load levels and constant (or changing) environmental conditions. Several analytical approaches show that plywood, OSB, and waferboard panels subjected to bending could meet or exceed NDS conventional DOL factors developed for clear wood in bending under dry environmental service conditions and constant loads.

Our attempts to model the creep–rupture behavior included several techniques. Predictions of creep–rupture behavior were obtained through DA and exponential time to failure models. Data from ramp-loaded to failure tests were used in the DA model, resulting in some parameter estimates with wide confidence limits. The best model estimates resulted from the DA and exponential models with constant-load data.

The 6-month creep performance of all three products was also comparable with lumber under dry service conditions. The observed trends, however, indicated that plywood, OSB, and waferboard, in that order, are more sensitive to environmental conditions than lumber.

To move composite wood products into specific structural end uses, engineers and designers need to have the confidence that these products will perform safely under all expected service loads and specified environmental conditions. To ensure this, wood-based panel products should be used in dry (selected) environmental conditions when deflection serviceability is crucial. For humid, wet, or cycling moisture environments, additional experimental and theoretical work is needed to establish general performance criteria for these products.

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Appendix: Gerhards–Link Cumulative Damage Model

This Appendix is a series of excerpts from Gerhards and Link (1987) that have been slightly edited to reflect this study. In the United States, design values for wood are based on normal loading, which implies a design load lasting for 10 years of either continuous or cumulative duration. Design values are adjusted upward for shorter durations of load (such as snow, wind, or earthquake) and downward for permanent (dead weight) loading. Recommended adjustments for loads of different duration are published by the American Forest and Paper Association (AFPA 1997).

These duration of load factors are based on a duration of load curve developed from rapid pseudo ramp-load and constant-load tests of small clear wood specimens in bending (Wood 1951). Wood's analysis of the data was based on the assumption that one continuous curve could be used in code applications to account for time to failure for both ramp loads and constant loads. That assumption is not strictly valid because the stress developed in a ramp-load test theoretically should be higher than the stress that can be carried in a constant-load test for equal time to failure. Such assumption is not required when duration of load is accounted for by a cumulative damage model.

The damage model (Gerhards 1977, 1979) relates damage accumulation exponentially to load. The model can be written as

$$d\alpha/dt = \exp[-a + bP(t)/P_s] \qquad \text{(A1)}$$

where α is the amount of damage (0 implies no damage, 1 implies failure), $d\alpha/dt$ is the rate of damage, $P(t)$ is the applied load history, a and b are parameters, and P_s is static strength. Equation (A1) can be integrated for any stress history $P(t)$, $t \geq 0$, to determine the accumulated damage α. The time to failure at $\alpha = 1$ will be designated as T.

In applying the damage model to panel strength and duration of load, we recognize that the static strength P_s varies from panel to panel for any population. For this study, we believe the lognormal distribution

$$P_s = P_0 \exp(wR) \qquad \text{(A2)}$$

provides an adequate description of this variation in static strength, where P_0 is the median strength, w is a measure of variability, and R is a standard (mean 0 and variance 1) normal random variable. When Equation (A2) is substituted into Equation (A1), the two parameters, b and P_0 appear as a fraction. Therefore, we introduce $b' = b/P_0$ and Equation (A1) becomes

$$d\alpha/dt = \exp[-a + b'P(t)/\exp(wR)] \qquad \text{(A3)}$$

with a, b', and w as the parameters to be estimated.

Two traditional load histories are used for duration of load testing of wood: ramp loading and constant loading. In ramp loading, $P(t) = kt$ where k is a constant. In constant loading, $P(t) = P_c$, a constant. Integration of Equation (A3) to failure yields

$$T = \exp[a - b'P_c/\exp(wR)] \qquad \text{(A4)}$$

for constant loading and

$$T = \frac{\exp wR}{b'k}\ln\left[\frac{b'k}{\exp wR}(\exp a) + 1\right] \qquad \text{(A5)}$$

for ramp loading. If the load history is a combination of periods of ramp loading and constant loading, each segment of the load history may be integrated and damage accumulated until failure occurs. The stress-rupture phase of this study involved a period of ramp loading until the desired level of constant load was attained, then a period of constant load to failure. Integration of Equation (A3) for ramp loading followed by constant loading to failure yields

$$T = \frac{P_c}{k} - \exp\frac{wR}{b'k} + \exp\frac{-b'P_c}{\exp wR}\exp\frac{wR}{b'k} + \exp a \qquad \text{(A6)}$$

Equation (A4) is an approximation of Equation (A6) when constant load time is long relative to the ramp loading time necessary to get to the constant load, as $\exp(wR)/(b'k)$ and P_c/k are small relative to T.

From Equation (A4), the constant load that causes failure is linearly related to the logarithm of the median time to failure through

$$P_c = (a - \ln T)/b' \qquad \text{(A7)}$$

Similarly, from Equation (A5), the median strength in ramp loading to failure, P_r is approximately linearly related to logarithm of rate of loading:

$$P_r \approx [a + \ln(b'k)]/b' \qquad \text{(A8)}$$

In estimating model parameters, a and b' were found to be very highly correlated with each other and to a lesser extent with w. Therefore, we substituted c for b'/a in estimating model parameters to decrease parameter correlations. Equation (A7) becomes

$$P_c = (b'/c - \ln T)/b' \qquad \text{(A9)}$$

and Equation (A8) becomes

$$P_r \approx [b'/c + \ln(b'k)]/b' \qquad \text{(A10)}$$

An iterative reweighed nonlinear least squares procedure was used to estimate the parameters c, b', and w. The dependent variable was $\ln T$ for all ramp-load failures. For specimens failing during constant load, the dependent variable was $\ln(T - T_1)$, time on constant load (total time T minus uploading time T_1). The independent variable was an estimate of the underlying standard normal random variable R which is unknown. The estimates of R are the expected values of the order statistic of a sample size n, from a standard normal distribution. Sample sizes in this study were 90 (30 × 3 loading rates or 30 × 3 stress levels) for plywood and OSB and 75 for waferboard.

Equation (11) in Gerhards and Link (1987), solved for P_c (where SL = P_c/P_0), becomes

$$P_c = \frac{-\ln(T - T_1 + 1/b'k) - \ln\left(\exp a + 1/b'k\right)}{b'} \qquad \text{(A11)}$$

Since T_1 (uploading time) is very small (<60 s) compared with total load time T for most usual DOL considerations (for example, 6 months, 10 years) and $1/(b'\text{k})$ is also very small (<0.025) compared with exp a ($>3 \times 10^9$), Equation (A11) becomes

$$P_c = (a - \ln T)/b' \qquad \text{(A12)}$$

which is the same as Equation (A7) (or Eq. (A9) with $a = b'/c$).

Equation (A9) was then used to calculate the DOL factors for the ramp-load data (Table 11) and for the constant-load data (Table 13):

$$\text{DOL factor} = \frac{(b'/c - \ln T_2)/b'}{(b'/c - \ln(T_1)/b'} \qquad \text{(A13)}$$

or

$$\text{DOL factor} = \frac{b' - c\ln T_2}{b' - c\ln T_1} \qquad \text{(A14)}$$

where T_1 = 5 min (300 s) and T_2 is time in seconds for 2 months or 10 years, with b' and c as model parameters determined from curve fitting to experimental data.

For example, the values for parameters b' and c from the constant-load data for Material O are $b'= 0.0680876$ and $c = 0.00174846$. For T_1 = 5 min, $\ln T_1 = 5.704$, and for T_2 = 2 months, $\ln T_2 = 15.461$.

$$\text{DOL factor} = \frac{0.0680876 - 0.00174846\,(15.461)}{0.0680876 - 0.00174846\,(5.704)} = 0.71$$

This is shown in Table 13 as the DOL factor for 2 months loading for Material O.

Since the DOL factor is a function of the baseline (5 min) and target times (2 months and 10 years) as well as the estimated parameters, confidence intervals can be obtained for the DOL factor using the estimated variability of the parameters b' and c and the following equation from the appendix of Link (1988):

$$\begin{aligned}\text{Standard error (DOL factor)} \\ &\equiv \text{sedol} \\ &= [(\text{se}c \times dc)^2 + (\text{se}b' \times db')^2 \\ &\quad + 2(rb'c \times \text{se}c \times dc \times \text{se}b' \times db')]^{1/2} \qquad \text{(A15)}\end{aligned}$$

where se$c$ is standard error of c; seb' is standard error of b'; $rb'c$ is correlation of b' and c; $dc = b'(\ln(T_2) - \ln(T_1))/(b' - c\ln(T_2))^2$; $db' = c(\ln(T_1) - \ln(T_2))/(b' - c\ln(T_2))^2$

The 95% confidence intervals for the DOL factor are then

$$\text{DOL factor} \pm 1.96\,(\text{sedol}) \qquad \text{(A16)}$$