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STATE-OF-THE-ART REPORT ON DURATION OF LOAD RESEARCH FOR LUMBER IN NORTH AMERICA

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This paper provides an overview of duration of load research for lumber in Canada and the United States to date. The research programs, recent results, and link of these results to previous results are summarized. The experimental data and calibrated linear and nonlinear damage accumulation models are presented. Finally, two approaches to developing load duration factors—the traditional stress ratio approach and a probabilistic approach—are discussed.

BACKGROUND

The duration of load (DOL) factor is important for both the design of wood members in working stress and the limit states design codes. Traditionally, DOL factors were expressed as stress ratios (ratio of applied constant stress to estimated short-term strength) for various load durations (for example, 2-month duration for snow loads). The DOL factors developed today are being based on a probabilistic approach that employs time history of load and strength distributions and damage accumulation models. Since the 1970s, researchers have been working on the DOL effects in full-size lumber, and the results are now being implemented in engineering design codes in North America.

LITERATURE REVIEW

In North America, the DOL factors were initially based on Wood's (1) work on small defect-free specimens, and they were applied to adjust the design stresses of lumber and other wood products as well as connections for different loading conditions. In Canada, the first DOL research on dimension lumber was carried out by Madsen (2), who tested No. 2 grade nominal 2- by 6-in. (standard 38- by 140-mm) Ben-Fir lumber under bending with several stepwise constant bending loading regimes. One of Madsen's conclusions was that the time effect in bending strength is dependent upon stress level. Later, Madsen and Barrett (3) and Foschi and Barrett (4) showed that the relationship between applied constant load and time to failure for small defect-free specimens differs from a similar relationship in full-size

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lumber, Gerhards (5) summarized the world literature up to 1976 on the effect of rate and DOL on wood and wood-based materials, and Karacabeyli (6) presented a literature survey on DOL research for lumber conducted up to 1986 in North America. In 1985, a total of 57 scientists and engineers exchanged information in an International Workshop (7) on Duration of Load in Lumber and Wood Products organized by Forintek Canada Corporation (Forintek). Since then, several researchers have conducted experimental DOL studies. Gerhards (8–10) presented results on the effects of high temperature drying, lumber grade, and repeated loads on DOL for Douglas Fir lumber. Soltis et al. (11,12) investigated the long-term strength of lumber treated with chromated copper arsenate (CCA) and the effect of loading mode on DOL factors. Karacaheyli (13) investigated the modes of failure for lumber under long-term bending loads, and Fridley et al. (14,15) examined the effect of cyclic temperature and cyclic relative humidity on the DOL behavior of lumber.

A comparison of the stress ratio data from Forintek and the Forest Products Laboratory (FPL) (Forest Service, United States Department of Agriculture) revealed some differences for a given constant load duration. A Comparison Testing Program (16) was established to account for these differences. For Canadian code implementation, Kararabeyli (6) obtained model parameters for the Foschi Yao damage accumulation model by calibrating the model to the available data for bending, tension, and compression loading modes. Using these model parameters and load and short-term strength distributions for bending loading mode, Foschi et al. (17,8) developed the DOL factors for the 1989 edition of the Canadian code for engineering design in wood (19). Kararabeyli (20) conducted the same analysis for lumber in tension loading mode. Foschi (21) discussed the advantages of the reliability-based approach compared to the traditional allowable design (working stress) approach in the design of wood structures.

In the United States, a load and resistance factor design (LFRD) code has been developed and is undergoing trial designs for engineered wood construction. Ellingwood et al. (22,23) performed reliability analysis using different damage accumulation models. A task committee of the American Society of Civil Engineers prepared a prestandard report (24) on the LFRD for wood construction. The U.S. and Canadian lumber industry sponsored a project for the development of a LFRD standard. Progress on this project was presented by Gromala et al. (25) and Goodman (26).

DURATION OF LOAD TEST PROGRAMS

In Canada, DOL studies on lumber were first conducted in the 1970s at the University of British Columbia (UBC) on nominal 2- by 6-in. (standard 38-y 140-mm) Hem-Fir and Douglas Fir lumber (2,3). Later, the DOL study on Western Hemlock lumber was conducted at Western Forest Products Laboratory of Canada and its successor, Forintek (4). In the United States, an edge-knot study (27) on nominal 2- by 4-in. (standard 38- by 89-mm) Douglas Fir lumber was the first DOL study on dimension lumber. A cooperative U.S.–Canadian DOL Test Program was formed under the U.S. Canada Light Frame Structures Research Program. Under this program, Forintek tested nominal 2- by 8-in. (standard 38- by 184-mm) Spruce lumber in bending and nominal 2- by 4-in. (standard 38- by 89-mm) Spruce lumber in bending, tension, and compression (6); the FPL tested nominal 2- by 4-in. (standard 38- by 89-mm) Douglas Fir lumber in bending, tension, and compression (12,28). Apart from this program, FPL also tested 2- by 4-in. (38- by 89-mm) Southern Pine and Douglas Fir lumber under different test conditions (8-11). Some test groups from the FPL samples were tested at the University of Auburn (14,15). For the Forintek–FPL Comparison Study, the nominal 2- by 4-in. (standard 38- or 89-mm) and nominal 2- by 6-in. (standard 38- by 140-mm) Douglas Fir lumber was sampled, conditioned, E-rated and grouped at FPL, and constant load tests were conducted at Forintek (16).

The Canadian DOL Review Committee consisted of representatives from the Canadian and U.S. lumber industries, Forintek, FPL, UBC, Johns Hopkins University, and Forestry Canada. The committee met at Forintek in September 1989 and reviewed the progress of DOL research studies undertaken at Forintek and the FPL. The committee recommended that the DOL test programs be completed and that all the test data be analyzed using a reliability-based approach. It also recommended that future research focus on shear and tension perpendicular-to-grain loading modes, cyclic loading conditions, crack propagation, and DOL effects on composite wood products, connections, and wooden structural systems.

The experiments conducted at Forintek and FPL are described in Tables 1 and 2. Bending specimens were tested on edge and under three-point loading at Forintek and under two-point loading (points 61 cm (2 ft) apart) at FPL. Fully restrained compression specimens are being tested such that the effective slenderness ratio for both centroidal axes is approximately 17 (10, 20). The constant tension load tests are being carried out in frames designed by Glos and Barrett (30). Further details of these test programs, such as sampling, matching, test setups, data acquisition systems, failure definitions, and test conditions, have been published (9–12, 28–32).

The environmental conditions in Forintek's DOL experiments are not controlled. However, the mild climate of British Columbia has not induced large variations in specimen moisture content. The oven-dry moisture content of the broken constant-load specimens at Forintek's long-term research facility varied between 7.5% and 11.5% during 1984–1990. The experiments at FPL are being conducted in controlled (23°C (73° F), 50% relative humidity) conditioning rooms. Specimen oven-dry moisture content ranges from 9.5% to 11.5%.

Time-to-failure data

For short-term strength, the cumulative frequency distribution reflects the variability of the test material. In a short-term strength distribution with high variability, the difference in strength values of $i^{\text{th}}-1$ and i^{th} specimens is larger than that of the strength distribution with low variability. Therefore, the i^{th} specimen in a constant load test group with high short-term strength variability has to undergo more strength degradation—consequently, this specimen will take longer time to fail than a specimen in a constant load test group with low short-term strength variability. This leads to the hypothesis that the cumulative frequency of the time-to-failure data for a constant load test group also reflects the variability of the material, and that the variability of time-to-failure is a function of variability of short-term strength. For example, in Figure 1, two groups with similar mean short-term values loaded at constant stress levels of 30.3 MPa (4,400 lb/in²) and 20.7 MPa (3,000 lb/in²), corresponding respectively to the 3rd and 5th percentiles of the matched control groups' strength distributions (short-term ramp test), had similar percentage of failures up to approximately 100 h. After 100 h, however, the specimens belonging to the group with low short-term strength variability started failing at a greater failure rate than that of the other group. The difference of time-to-failure data for these groups can also be seen in a real time scale (Fig. 2), which gives a different perspective for the trend of constant load failures than that of a logarithmic scale. The allowable stresses in working stress design codes or specified strength values in limit state design codes are based on the characteristic strength values (usually the 5th percentile of short-term strength distribution). Although the material with low short-term strength variability has the advantage of having a higher characteristic strength than material with high short-term strength variability, it may be more susceptible to DOL effects. This has importance especially for composite wood products, machine stress rated lumber, and connections.

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Table 1. Properties of control (short-term) groups and applied constant stress levels for long-term Forintek-FPL study^a

Test category ^b	Control			Group I			Group II		
	Mean MOR (MPa)	STD (MPa)	Ramp rate (MPa/s)	Stress level ^c (MPa)	Specimens (no.)	Time of load	Stress level ^c (MPa)	Specimens (no.)	Time of load
2x6 #2 H ¹									
B	47.83	19.53	0.7439	31.03 (20)	500	3m-4y	20.68 (5)	500	3m-4y
2x8 Q1 S ¹									
T	46.42	10.16	0.7433	36.54 (16)	150	1y	30.34 (6)	75	3y
C	51.28	8.92	0.7433	36.54 (7)	150	1y	30.34 (1)	75	3y
B,T,C	48.90	9.83	0.7433	36.54 (11)	300	1y	30.34 (3)	150	3y
2x8 Q2 S ¹									
T	22.95	5.32	0.4578	18.13 (20)	150	1y	15.65 (6)	75	3y
C	28.54	7.54	0.4578	18.13 (6)	150	1y	15.65 (4)	75	3y
B,T,C	25.77	7.09	0.4578	18.13 (13)	300	1y	15.65 (5)	150	3y
2x4 Q3 S ²									
T	23.56	7.90	1.660	16.41 (16)	150	10m	15.65 (12)	75	3y ^d
C	31.27	10.37	1.660	16.41 (2)	150	10m	15.65 (1)	75	3y ^d
B,T,C	27.33	9.89	1.660	16.41 (9)	300	10m	15.65 (7)	150	3y
2x4 Q3 S ²									
C	25.63	5.63	0.7357	17.37 (5)	300	7m	14.48 (1)	150	3y ^d
2x4 Q3 S ³									
T	15.48	4.10	0.2737	11.31 (17)	298	1y	8.96 (5)	148	3y
2x6 DF ¹									
B	29.13	11.93	0.4116	24.56 (40)	100	2y	18.03 (20)	100	2y
2x4 DF ²									
B	46.77	17.51	0.1179	29.72 (18)	50	2y ^d	8.96 (5)	148	3y

Abbreviations: DF is Douglas Fir, H Hemlock, S spruce. B is bending, C compression, T tension. STD is standard deviation. Time of load-m is months, y years.

^aData for Group III are for bending tests of 2x6 DF: 11.86 MPa, 5th percentile, 100 specimens, 2-year time of load

^bLumber dimensions: nominal 2 by 4, 2 by 6, and 2 by 8 in. (standard 38 by 89, 38 by 140, and 38 by 184 mm). Q1, high quality, bending strength ratio 0.60-0.95; Q2, low quality, bending strength ratio 0.20-0.60; Q3, medium quality, bending strength ratio 0.40-0.60. Tension and compression specimens tested in edgewise third-point bending with worst edge defect in tension and compression zones, respectively. For bending tests, specimen length is center to center span; for compression, full length; for tension, length between grips of test machine. Superscript numbers refer to specimen length, ¹3,505 mm (138 in.), ²1,600 mm (63 in.), ³2,286 mm (90 in.).

^cNumber in parentheses is percentile 1 MPa = 145 lb/in.

^dOngoing experiment.

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Table 2. Properties of control (short-term) groups and applied constant stress levels for long-term FPL experiments^a

Test category ^b	Control			Group I		Group II		Group III	
	Mean MOR (MPa)	STD (MPa)	Ramp rate (MPa/s)	Stress level ^c (MPa)	Specimens (no.)	Stress level ^c (MPa)	Specimens (no.)	Stress level ^c (MPa)	Specimens (no.)
Loading									
DF B ¹	33.47	12.62	0.1689	13.56 (1)	100	16.69 (5)	100 ^d	20.48 (15)	100 ^e
T ²	20.55	5.38	0.0931	8.65 (1)	100	13.31 (7)	100 ^d	15.10 (18)	100 ^e
C ³	30.06	3.96	0.1689	18.64 (2)	100	23.30 (7)	100 ^d	25.44 (19)	100 ^e
Grade^{1,f}									
DF B SS	43.88	16.15	0.1689	—	150	—	150	—	150
#2	22.18	8.13	0.1689	—	150	—	150	—	150
#3	16.99	6.27	0.1689	—	100	—	100	—	100
Temp-Dry^{1,g}									
DF B CD	10.71	2.14	0.1689	28.44 (10)	50 ^h	47.97 (40)	50 ^h	—	—
HTD	9.39	1.88	0.1689	28.44 (10)	50 ^h	47.97 (40)	50 ^h	—	—
HTD^{1,g}									
SYP B	34.99	14.37	0.1689	16.29 (5)	50	22.73 (20)	50	29.37 (40)	50
CCA^{1,g}									
SYP B	44.33	23.65	0.1689	16.82 (10)	50 ^h	33.51 (40)	50 ^h	—	—

Abbreviations: DF is Douglas Fir, SYP southern yellow pine. SS is Select Structural. B is bending, C compression, T tension. Temp Dry in temperature-drying study, CD conventional drying, HTD high-temperature drying CCA is chromated copper arsenate. STD is standard deviation.

^aAll tests used nominal 2- by 4-in. (standard 38- by 89-mm) lumber.

^bSuperscript numbers refer to specimen length: ¹2,134 mm (84 in.), ²2,438 mm (96 in.),

³1,562 mm (62 in.).

^cNumber in parentheses is percentile. 1 MPa = 145 lb/in.

^dLoad duration of 3 years.

^eLoad duration of 9 months.

^fStep-applied loads were at various stress levels.

^gOnly base level drying and untreated group results are given.

^hLoad duration of 3 months.

Examples of time-to-failure data collected at Forintek and FPL are shown in Figures 3 to 6 in both logarithmic and real time scales.

Stress ratio approach

Because it is difficult to establish DOL factors using only the cumulative frequency of time-to-failure data, these factors have traditionally been established by using the stress ratio (ratio of applied constant stress to estimated short-term strength) approach. Stress ratios were determined by the Equal Rank Assumption, which assumes that the order of failure for constant load test specimens is the same as that for short-term (control) ramp load test specimens (Fig. 7). Using this approach, stress ratios were calculated for all bending groups tested at Forintek and FPL (Table 3). Stress ratios for Douglas Fir tested at FPL

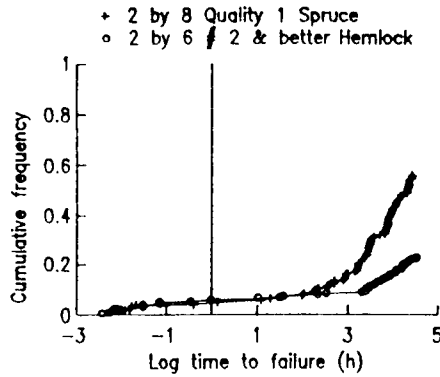


Figure 1 Short-term strength variability (logarithmic time). For Spruce, constant stress level was 30.3 MPa (4,400 lb/in²), mean MOR 48.8 MPa (7,093 lb/in²), and standard deviation 9.8 MPa (1,425 lb/in²). For Hemlock, constant stress level was 20.7 MPa (3,000 lb/in²), mean MOR 47.8 MPa (6,937 lb/in²) and standard deviation 19.5 MPa (2,833 lb/in²).

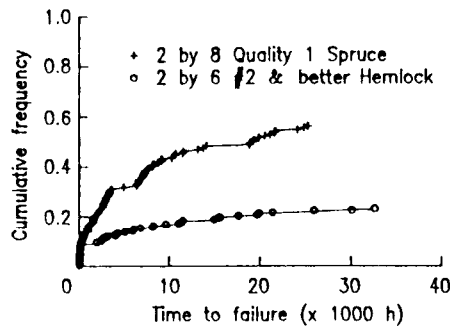


Figure 2. Short-term strength variability (real time) For Spruce, constant stress level was 30.3 MPa (4,400 lb/in²), mean MOR 48.8 MPa (7,093 lb/in²) and standard deviation 9.8 MPa (1,425 lb/in²). For Hemlock, constant stress level was 20.7 MPa (3,000 lb/in²), mean MOR 47.8 MPa (6,937 lb/in²), and standard deviation 19.5 MPa (2,833 lb/in²).

were found to be smaller than those for Spruce and Hemlock lumber tested at Forintek and Southern Pine lumber tested at FPL. A Comparison Testing Program was established to find out the reason or reasons for the differences. Results from this program are also shown in Table 3. The stress ratios found for Douglas Fir lumber in this program are consistent with the results of Douglas Fir studies conducted at the FPL. Analysis of data from tension and compression constant load experiments from Forintek and FPL are still in progress. Glos (33) concludes that the magnitude of DOL effect for European spruce in tension and compression loads is close to that shown in the Madison curve (Fig. 8). Similar trends in preliminary data analysis were also observed by Karacabeyli (6) and Soltis et al. (12). The stress ratios for European whitewood (34) and Douglas Fir (3) lumber (from interior British Columbia) loaded in bending are in close agreement with the stress ratios for Canadian Hemlock and Spruce lumber. The average stress ratios from Forintek and FPL constant bending load studies are shown in Figure 8 along with ratios from European whitewood and UBC Douglas Fir studies and the Madison curve (1).

Table 3. Stress ratios for lumber in bending load mode.

Research site and study	Stress ratios for various durations of load									
	Day	Week	Month (no.)						24	36
			1	2	3	6	12			
Forintek										
S & H (min) ^a	0.80	0.77	0.75	0.72	0.71	0.68	0.62	0.60	0.57	
(avg)	0.93	0.87	0.82	0.80	0.77	0.73	0.69	0.64	0.62	
(max)	1.03	1.00	0.93	0.89	0.87	0.83	0.73	0.68	0.67	
Comp DF (min)	0.73	0.68	0.61	0.57	0.55	0.51	0.49	0.47	—	
(avg)	0.77	0.73	0.67	0.62	0.60	0.56	0.53	0.51	—	
(max)	0.82	0.79	0.72	0.67	0.64	0.58	0.55	0.53	—	
FPL										
DF (min) ^b	0.74	0.66	0.60	0.56	0.55	0.51	0.48	—	—	
(avg)	0.79	0.72	0.67	0.64	0.63	0.60	0.58	—	—	
(max)	0.86	0.78	0.73	0.72	0.71	0.69	0.68	—	—	
SP HTD (avg)	0.86	0.82	0.80	0.78	0.78	—	—	—	—	
SP CCA (avg)	0.84	0.80	0.76	0.75	0.74	—	—	—	—	

Abbreviations: DF is Douglas Fir, SP Southern Pine, S & H Spruce and Hemlock. Comp is Comparison Testing Program. HTD is high-temperature drying, CCA chromated copper arsenate.

^aThree qualities of Canadian white spruce, No. 2 and better Western Hemlock, and two sizes (nominal 2 by 4 and 2 by 8 in. (standard 38 by 89 and 38 by 184 mm, respectively)).

^bEdge knot, 3,600 specimens. 1,000-specimen samples.

Test results indicate that some survivors of the constant load experiments underwent a strength degradation. Karacabeyli (6) showed that the nominal 2 by 8 in. (standard 38 by 184 mm) Spruce specimens with short-term strength equal to or greater than twice the constant stress level did not suffer a strength loss. This conclusion is consistent with the threshold stress ratio (stress level that must be exceeded for damage to accumulate) that will be determined later as one parameter in the Foschi-Yao damage accumulation model. The creep values in the constant load experiments were also measured and were reported previously (35,36).

Damage accumulation models

When reliability analysis is performed to develop DOL factors for lumber under certain loads—dead load, dead plus snow loads, and dead plus occupancy loads—the load distributions used are not necessarily the constant loads used in DOL experiments. To assess the strength degradation in lumber under varying loads, damage accumulation models or fracture mechanics models (37) were developed in the past decade. In this paper, models by Foschi-Yao (17) and Gerhards (27) were calibrated to some DOL data sets.

The Foschi-Yao model is expressed as

$$\frac{d\alpha}{dt} = a[\tau(t) - \sigma_0 \tau_s]^b + c[\tau(t) - \sigma_0 \tau_s]^n \alpha$$

where α is a damage state variable that is 0 at, initial state and 1 at failure; b , c , n and σ_0 (threshold stress ratio) are four model parameters that are assumed to be constants for a

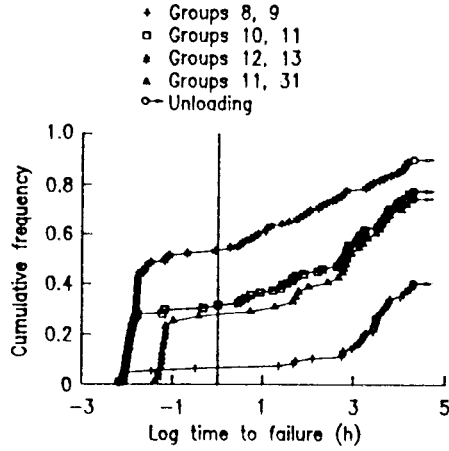


Figure 3. Forintek duration of load (DOL) data (logarithmic time). Groups 8-13, Douglas Fir nominal 2- by 6-in. (standard 38- by 140-mm) lumber. Groups 11 and 31, Douglas Fir nominal 2- by 4-in. (standard 38- by 89-mm) lumber.

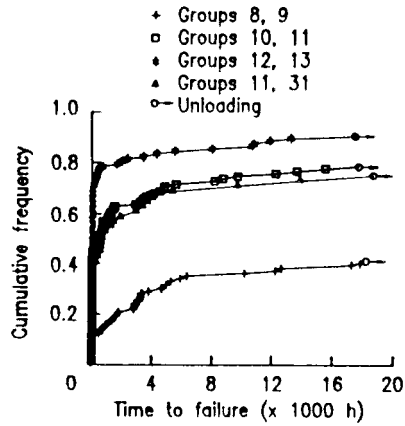


Figure 4. Forintek duration of load (DOL) data (real time). Groups 8-13, Douglas Fir nominal 2- by 6-in. (standard 38- by 140-mm) lumber. Groups 11 and 31, Douglas Fir nominal 2- by 4-in. (standard 38- by 89-mm) lumber.

given structural member but vary randomly across the members; τ_s is short-term strength; $\tau(t)$ is applied stress at time t ; and a is another model parameter determined as a function of the other parameters. Foschi et al. (17) provided a detailed description and calibration of the model: The Foschi-Yao damage accumulation model parameters are given in Table 4, and Figure 9 shows an example of model fit. In developing Table 3, the four independent parameters and short-term strength were assumed lognormally distributed.

Table 4. Mean and standard deviation of Foschi-Yao damage accumulation model parameters^a

Test category ^b	b		c		n		σ ₀	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
2 by 6 Hemlock	37.161	10.430	0.2465×10 ⁻⁶	0.8294×10 ⁻⁷	1.290	0.097	0.533	0.159
2 by 8 Q1 Spruce	26.200	5.011	0.1452×10 ⁻²	0.2901×10 ⁻³	0.164	0.029	0.601	0.030
2 by 4 Q2 Spruce	73.332	1.150	0.3250×10 ⁻⁵	0.4959×10 ⁻⁶	1.155	0.137	0.502	0.134
2 by 4 Spruce	168.088	56.348	0.4947×10 ⁻⁶	0.1521×10 ⁻⁷	1.392	0.606	0.407	0.257
2 by 6 & 2 by 4 Douglas Fir	11.000	2.200	0.1500×10 ⁻²	0.3000×10 ⁻³	0.140	0.028	0.510	0.102

Abbreviations: Q1, high quality, bending strength ratio 0.60-0.95; Q2, low quality, bending strength ratio 0.20-0.60. STD is standard deviation.

^a Units used in calibration: lb/in² for stress, lb/in²/h for short-term loading rate
 1 lb/in² = 6.89 kPs.

^b All bending tests. Lumber dimensions: nominal 2 by 4, 2 by 6, and 2 by 8 in. (standard 38 by 89, 38 by 140, and 38 by 184 mm).

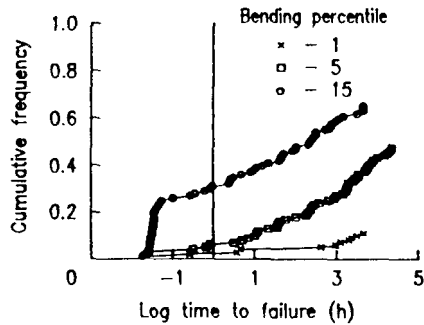


Figure 5. FPL duration of load data (logarithmic time).

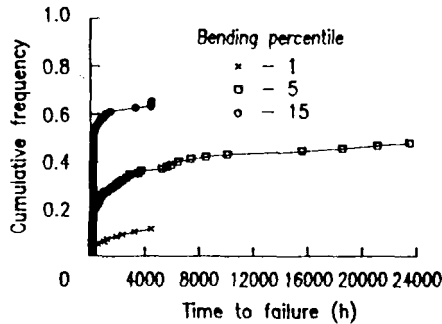


Figure 6. FPL duration of load data (real time).

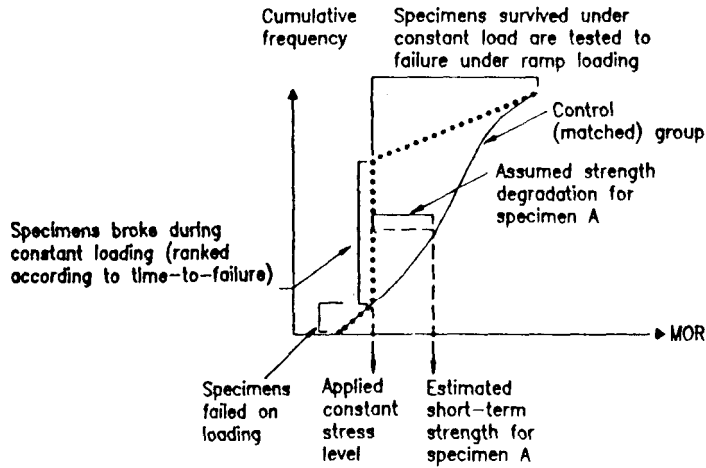


Figure 7. Determination of stress ratio.

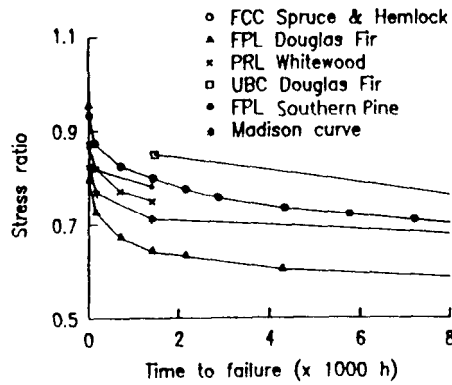


Figure 8. Average stress ratios for lumber in bending (real time). FCC is Forintek Canada Corporation, FPL Forest Products Laboratory, PRL Prince Risborough Laboratory, UBC University of British Columbia.

The Gerhards model is expressed as

$$\frac{d\alpha}{dt} = \exp\left(-a + b \frac{\tau(t)}{\tau_s}\right)$$

where a and b are model parameters, τ_s is short-term strength, and $\tau(t)$ is applied stress. The detailed description and calibration of the model are given in reference 27. The Gerhards model parameters for some experimental treatment groups are given in Table 5, and Figure 10 shows an example of model fit.

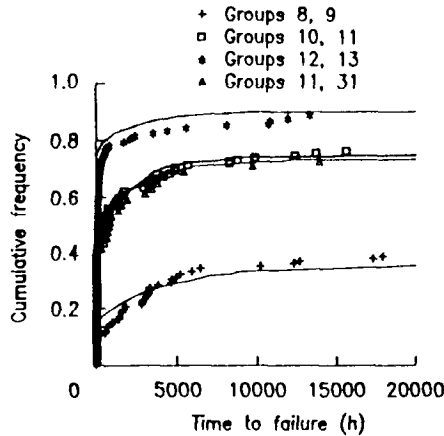


Figure 9. Foschi-Yao model fit to Comparison Study data from Douglas Fir nominal 2- by 4-in. (standard 38- by 89-mm) and nominal 2- by 6-in. (standard 38- by 140-mm) lumber.

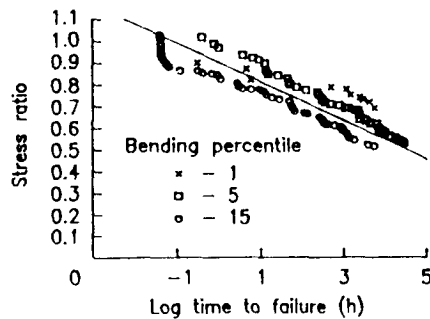


Figure 10. Gerhards-Link model fit to bending data from Douglas Fir nominal 2- by 4-in. (standard 38- by 89-mm) lumber.

CODE IMPLEMENTATION

The DOL factor in the 1989 edition of the Canadian engineering design code for wood (19) was developed for lumber using a probabilistic approach (17) that accounted for the variability in loads and strength as well as damage accumulation in wood caused by loads. The reliability-based calculations showed that a common DOL factor may be applied to design equations applicable to both the dead plus snow toad and dead plus floor toad combinations. The strength limit state design equation for the combination of dead and live loads is

$$1.25D + 1.5L = \phi Kd f \text{ (other factors)}$$

where *D* is specified dead load, *L* is specified occupancy or snow loads, ϕ is performance factor, *Kd* is DOL factor (Table 6), and *f* is 5th percentile specified strength value for

Table 5. Mean and standard deviation of Gerhards-Link damage model parameters

Test category	a		b	
	Mean	STD	Mean	STD
2 by 4 Douglas Fir ^a				
Bending	28.8	0.6	27.4	0.8
Tension	34.2	0.5	36.8	0.6
Compression	44.1	0.3	45.9	0.3

Table 6. Load duration factors (*Kd*) in CSA-CAN3-086.1-M89 (19)

Duration of load	<i>Kd</i>	Explanatory notes
Short term	1.15	Duration of specified loads is not more than 7 days, continuous or cumulative. Examples: wind, earthquake, falsework, formwork, impact loads.
Standard term	1.00	Duration of specified loads exceeds that of short-term loading but less than that of permanent loading. Examples: dead load plus snow or occupancy load, wheel loads on bridges.
Permanent	0.65	Duration of specified loads is more or less continuous. Examples: tanks containing granular material, retaining walls subject to lateral pressure, loads caused by fixed machinery.

“standard term” load duration, which is 80% of the 5th-percentile strength value obtained in a 1- to 10-min ramp loading test.

The strength limit state design equation for the combination of dead and live loads in the proposed LFRD standard in the United States is

$$1.20D + 1.6L = \phi Kdf \text{ (other factors)}$$

where the load factors are slightly different than those used in Canada. The time effects factor *Kd* was developed based on a probabilistic approach (23) and is given in Table 7. The strength value *f* is a short-term (5-min) value and thus differs from that used in Canada. However, the product of strength values and DOL factors are similar in Canada and the United States. Gromala et al. (25) discussed the technical judgment embodied in the recommended LFRD procedures. These authors indicated that the DOL factors (time effect factors) in LFRD are in close agreement with Canadian, Eurocode, and New Zealand timber design codes.

The probabilistic approach to the design of wood structures leads to a consistent limit states design because it includes adequate material properties, load distributions, and service history. This simplifies the design of wood structural members when they are mixed with members of other materials. For lumber, the short- and long-term data were collected

Table 7. Time effects factor in proposed U.S. LRFD specification

Load type	Kd
Dead	0.6
Live	
Impact	1.25
Storage occupancy	0.6
Other occupancies	0.8
Snow	0.8
Wind	1.0
Earthquake	1.0

and used to develop reliability-based DOL factors. These factors are also being applied to other wood products and connections. However, two wood products with identical short-term strength distributions do not necessarily behave the same way under long-term loads. Therefore, the long-term behavior of structural composite wood products and connections must be evaluated in a way that employs reliability-based design for entire wood structures. As a start, available DOL data can be collected for structural wood composites and fasteners.

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REFERENCES

1. Wood, L. Relation of Strength of Wood to Duration of Load. Res. Rep. 1916. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 1951.
2. Madsen B. Duration of Load Tests for Dry Lumber in Bending. S.R.S. Rep. No. 3. Vancouver, Can: Department Civil Engineering, University of B.C., 1971.
3. Madsen, B and Barrett, JD. Time-Strength Relationship for Lumber. S.R.S. Rep. No. 13. Vancouver, Can: Department Civil Engineering, University of B.C., 1976.
4. Foschi, RO and Barrett, JD. Load-Duration Effects in Western Hemlock Lumber. ASCE, Journal Structural Division 108(ST7):1494-510, 1982.
5. Gerhards, CC. Effect of Duration and Rate of Loading on Strength of Wood and Wood-Based Materials. Res. Rep. FPL 283. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 1977.
6. Karacabeyli, E. Duration of Load Research for Lumber in North America. In: Proceedings, International Timber Engineering Conference; Seattle, WA., U.S.A.: 380-389, 1988.
7. Proceedings of the International Workshop on Duration of Load in Lumber and Wood Products. Special Publication No. SP-27. Vancouver, British Columbia, Can: Forintek Canada Corporation, 1986.

8. Gerhards, CC. Effect of High-Temperature Drying on Bending Strength and Load Duration of Douglas-Fir 2 by 4's. *Forest Products Journal* 38(4):66-72, 1988.
9. Gerhards, CC. Effect of Grade on Duration of Douglas-Fir Lumber in Bending. *Wood Fiber Science* 20(1):146-161, 1988.
10. Gerhards, CC. A Note on Load Duration of Douglas-Fir 2 by 4s Under Repeated Loads. *Wood Fiber Science* 20(3):365-369, 1988.
11. Soltis, AL and Winandy, JE. Long-Term Strength of CCA-Treated Lumber. *Forest Products Journal* 39(5):64-68, 1989.
12. Soltis, AL, Nelson, W, and Hillis, JL. Effect of Loading Mode on Duration of Load Factors. In: *Proceedings, Second Pacific Timber Engineering Conference; Auckland, New Zealand, 1989.*
13. Karacabeyli, E. Discussion on Modes of Failure for Lumber Under Long-Term Bending Loads. In: *Proceedings, IUFRO/S5.02 Timber Engineering Group Meeting; St. John, NB, Can, 1990.*
14. Fridley, KJ, Tang, RC, and Soltis, LA. Effect of Cyclic Temperature on Duration of Load of Solid Lumber in Bending. In: *Proceedings, 3rd Joint ASCE/ASME Mechanics Conference; San Diego, NY, U.S.A., 1989.*
15. Fridley, KJ, Tang, RC, and Soltis, LA. Effect of Cyclic RH on the Load Duration Behavior of Structural Lumber. In: *Proceedings, International Timber Engineering Conference; Tokyo, Japan, 1990.*
16. Karacabeyli, E. Comparison Testing for U.S./Canada DOL Test Program: Second Report to Forestry Canada. Vancouver, British Columbia, Can: Forintek Canada Corporation, 1990.
17. Foschi, RO, Folz, BR, and Yao, FZ. Reliability-Based Design of Wood Structures. S.R.S. Rep. No. 34. Vancouver, Can: Department Civil Engineering, Univ. of BC, 1989.
18. Foschi, RO, Folz, BR, and Yao, FZ. Reliability-Based Design of Timber Structures—Canadian Results. In: *Proceedings, International Timber Engineering Conference; Tokyo, Japan: 302-310, 1990.*
19. Canadian Standards Association. CSA/CAN3-M89.086.1. Engineering Design in Wood. Rexdale, Canada, 1989.
20. Karacabeyli, E. Duration of Load Adjustment Factors for Lumber in Tension, Dead/Snow Loads. Report prepared for Canadian Wood Council Lumber Properties Steering Committee. Vancouver, BC, Can: Forintek Canada Corporation, 1987.
21. Foschi, RO. Reliability-Based Design in Timber Engineering. A Canadian Perspective. In: *Proceedings, International Timber Engineering Conference; Tokyo, Japan: 1-5, 1990.*
22. Ellingwood, BE, Hendrickson, EM, and Murphy, JF. Load Duration and Probability Based Design of Wood Structural Members. *Wood Fiber Science* 20(2):250-265, 1988.
23. Ellingwood, B and Rosowsky, D. Duration of Load Effects in LRFD for Wood Construction. New York: American Society Civil Engineering, *Journal Structural Engineering* 117(2):584-599, 1991.
24. ASCE. Load and Resistance Factor Design for Engineered Wood Construction. A Pre-Standard Report. New York: American Society Civil Engineering, 1988.
25. Gromala, DS, Sharp, DJ, Pollock, DG, and Goodman, JR. Load and Resistance Factor Design for Wood: The New U.S. Wood Design Specification. In: *Proceedings, International Timber Engineering Conference, Tokyo, Japan: 311-318, 1990.*

26. Goodman, JR. Reliability-Based Design for Engineered Wood Construction. Update and Status of U.S. Progress. In: Proceedings, International Timber Engineering Conference, Tokyo, Japan: 6-11, 1990.
27. Gerhards, CC, and Link, C. Use of a Cumulative Damage Model to Predict Load Duration Characteristics of Lumber. IUFRO Div. 5 Conference, Madison, WI, U.S.A., 1983.
28. Gerhards, CC. Duration of Load Research on Lumber at the U.S. Forest Products Laboratory. In: Proceedings, International Workshop on Duration of Load in Lumber and Wood Products; Richmond, BC, Can, 1985.
29. Samson, M and Olson, L. Apparatus for Long-Term Testing of Dimension Lumber in Compression Parallel to Grain. Forest Products Journal 37(1):44-46, 1987.
30. Glos, P and Barrett, JD. Machine for Duration-of-Load Tension Test of Dimension Lumber. Tech. Rep. No. 15. Vancouver, BC, Can: Forintek Canada Corporation, 1980.
31. Karacabeyli, E. Duration of Load Effects in Lumber in Bending, Tension, and Compression: An Analysis Report on the Up-to-Date Experimental Data. Report to Forestry Canada. Vancouver, BC, Can: Forintek Canada Corporation, 1987.
32. Samson, M. Duration of Load Effects in Spruce Lumber in Bending. Data Report—First Year. Report to Forestry Canada. Vancouver, BC, Can: Forintek Canada Corporation, 1983.
33. Glos, P. Creep and Lifetime of Timber Loaded in Tension and Compression. In: Proceedings, CIB W18/IUFRO S5.02; Florence, Italy, 1986.
34. Fewel, AR. 1985. Testing and Analysis Carried Out as Part of the Princes Risborough Laboratory's Program to Examine the Duration of Load Effect on Timber. In: Proceedings, International Workshop on Duration of Load in Lumber and Wood Products; Richmond, BC, Can, 1986.
35. Soltis, LA, Nelson, W, and Hillis, JL. Creep of Structural Lumber. In: Proceedings, 3rd Joint ASCE/ASME Mechanics Conference; San Diego, NY, U.S.A., 1989.
36. Karacabeyli, E, Varoglu, E, Deacon, B, and Stroh, L. Creep of Lumber in Bending Under Constant Load (in preparation).
37. Nielsen, LF. Wood as a Cracked Viscoelastic Material. Parts I and II. In: Proceedings, International Workshop on Duration of Load in Lumber and Wood Products; British Columbia, Can, 1985.