# DURATION OF LOAD BEHAVIOR OF LUMBER UNDER DYNAMIC LOADING

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ABSTRACT

The performance of structural wood members has proven to be generally satisfactory during dynamic load events such as earthquakes or severe wind conditions. The reasons for this, however, are not well understood as few data are available relative to dynamic member performance. Therefore, the true level of safety or conservatism in design is not only unknown, but cannot be accurately estimated with our current level of understanding. Procedures used to adjust member design values for cyclic dynamic loadings are not founded in robust behavior models or experimental test data, but rather experiential inference from past performance and static test data. Duration-of-load factors historically used in design were derived from a model developed from static, pseudo-static, and impact tests performed on small, clear-wood specimens. Other models and design factors have been developed subsequent to this; however, none of the models or design factors have been validated for cyclic dynamic load events such as those attributable to earthquakes and high winds. The present study attempts to partially address this shortcoming through an extensive experimental program. The results of the investigation provide data needed to develop robust behavior models and allow empirical assessment of current design factors. The data indicate the current duration-of-load factor in the NDS and time-effects factor in the LRFD for short duration dynamic loadings appear reasonable.

*Keywords:* Lumber, wood, dynamic loading, testing, design, behavior, creep-rupture, duration of load, damage, failure, bending.

## INTRODUCTION

The design of wood structures is prescribed by the National Design Specification (NDS) for Wood Construction (National 2001) for allowable stress design (ASD) and the Standard for Load and Resistance Factor Design for Engineered Wood (Standard 1996; LRFD 1996) using the load and resistance factor design (LRFD) method. In either case, the design strength of a structural member is adjusted for the duration of applied loading. The NDS tabulates nominal design values for an assumed ten-year cumulative load duration and duration-of-load adjustment factors for other assumed cumulative duration of loads. For example, the ten-year design strength is multiplied by a duration-of-load factor, $C_D$, of 0.9 for dead (or permanent) load, 1.15 for snow load, and 1.6 for wind and earthquake load. The LRFD uses a slightly different approach, but one that is based on the same principles. The design values published for the LRFD are based directly on the short-term capacity and are reduced for longer duration loads based on the load combination under consideration. For example, the nominal design capacity is multiplied by a time-effects factor, $\lambda$, of 0.6 for the ‘‘dead load only’’ LRFD combinations (i.e., $1.4D$), 0.8 for LRFD load combinations dominated by gravity loads (e.g., $1.2D + 1.6L$ or $1.2D + 1.6S$), and 1.0 for LRFD load combinations involving wind and earthquake loads (e.g., $1.2D + 1.3W$ or $1.2D + 1.0E$).

A considerable amount of research has been conducted in recent years to model the duration-of-load (or creep-rupture) behavior in structural wood members and to develop, modify, and/or confirm design factors such as those described above. However, one area that has not been explicitly or adequately addressed relative to duration-of-load behavior is the effect of cyclic dynamic loading on strength. Implicit in both the NDS and LRFD approaches is the assumption that the capacity of a wood member under a cumulative, design-level seismic or wind load is equivalent to its short-term (static) capacity.

The primary objective of this paper is to provide a basic understanding of the behavior of structural lumber subjected to cyclic dynamic loads through an extensive experimental effort. This was achieved by investigating the effects of cyclic dynamic loading on two sample populations of Douglas-fir 2 by 4 (38-mm by 89-mm) lumber. Both sample populations were part of larger populations of material utilized in previous duration-of-load research efforts (Gerhards 1988; Gerhards and Link 1987). In the present study, the lumber was subjected to various dynamic cyclic load histories and survivors were ramp-loaded (pseudo-static) to failure. These load tests allowed for comparisons between initial (virgin) properties, behavior during dynamic loading, and post-dynamic (residual) properties. This, in turn, provided a basis for characterizing the behavior of the lumber subjected to dynamic loading and for assessing the appropriateness of current design factors.

## BACKGROUND

A relationship between the failure of wood and the rate and duration of load has been recognized for several centuries (Fridley et al. 1995). This relationship, commonly referred to as duration-of-load effects, is a result of the creep-rupture phenomenon. Duration-of-load effects imply that a member may fail at a load less than its short-term strength if the load is sustained for an extended period. Even as early as the 1700s, duration-of-load effects had been investigated; however, it was not until the early 1950s that the first quantitative evaluation of duration-of-load effects was reported (Wood 1951).

Wood (1951) tested small, clear-wood samples in bending using static loads. From the tests, data were collected and analyzed, and a model was subsequently developed that described the relationship between the time-to-failure and the level of applied stress. This relationship, often referred to as the ‘‘Madison Curve,’’ has been used to develop duration-of-load strength adjustment factors that are still used in the design of engineered wood structures. However, the applicability and validity of using the Madison Curve, a model developed from tests performed on small clear-wood samples, to represent the response of structural size members have been questioned. Subsequently, experimental studies were conducted on the duration-of-load response of structural-size members, specifically dimension lumber (e.g., Foschi and Barrett 1982; Gerhards 1988, 2000; Gerhards and Link 1987; Madsen 1973; Madsen and Barrett 1976). The experimental plans for these research studies involved various combinations of ramp, constant, and step-constant load histories. As a result of these research efforts, the relationship between small clear duration-of-load behavior and that of structural-size members was established. Furthermore, new models have been developed to better predict the duration-of-load effects in lumber due to static loading (Barrett and Foschi 1978a, b; Foschi and Yao 1986; Fridley et al. 1992c; Gerhards 1979).

It is currently assumed that the observed static behavior and developed duration-of-load models are applicable and valid for predicting behavior under dynamic loading scenarios. Much is known about the behavior of other materials, such as steels, alloys, and various composite materials subjected to both static and dynamic loads. Many different tests have been conducted on structural lumber over the last four decades; however, the focus has been nearly exclusively on the behavior of lumber subjected to static loading. The dynamic cyclic loading of lumber has typically been ignored. It has been simply assumed that the behavior pattern will be similar regardless of the type of loading and, therefore, the factors developed are applicable.

## PREVIOUS RELATED RESEARCH

The lumber used in this study is part of a population of material that has been utilized in various research efforts spanning the last two decades in cooperation with the U.S. Forest Products Laboratory (FPL). The common purpose of the various research efforts has been to investigate duration-of-load effects in lumber. The particular portion of ongoing research reported herein focuses on duration-of-load effects in lumber subjected to cyclic dynamic loading. In this component of the investigation, two groups of lumber were tested. The first group consisted of edge-knot lumber and the second group consisted of in-grade lumber.

Prior to the present study, all material had been nondestructively evaluated and sorted into ''like'' groups based on material properties. Therefore, distributions of the modulus of elasticity, strength ratio, and predicted modulus of rupture were assumed equivalent between groups of similar material. In addition to this, static strength data were obtained for groups of material for various ramp, step-constant, and repeated sustained load histories and were available to form direct comparison with data from this study. The research from the current study draws heavily from two investigations (i.e., Gerhards and Link 1987; Gerhards 1988, 2000) in which duration-of-load effects were studied using static-type loads only. Following is background information, including test procedures and loads used by Gerhards and Link (1987) and Gerhards (1988, 2000), on the two samples of lumber acquired.

### *Gerhards and Link: Edge-knot lumber*

Gerhards and Link (1987) conducted sustained load tests on the parent population of edge-knot material. The edge-knot material was selected such that each specimen would contain in the central 610-mm length a nearly cylindrical knot of 25.4 mm to 34.9 mm in diameter. This strength-controlling edge knot was located at the edge of the wide face, but otherwise the member was free of knots. The material was 2 by 4 (38 mm by 89 mm), 2 by 6 (38 mm by 140 mm), and 2 by 8 (38 mm by 190 mm), cut to 3.44 m in such a way as to ensure that the edge-knot criterion listed above was satisfied but otherwise following the No. 1 lumber grade according to the WWPA (Western 1979) grading rules. All material was nondestructively evaluated, re-graded, and sorted into groups of 50 such that each group was statistically similar.

For the Gerhards and Link (1987) duration-of-load evaluation, each board was loaded in a 4-point (2 supports with 2 load-points) manner where the span between the two outer supports was 2.13 m and the load was applied at two points symmetrically located about midspan and 610 mm apart. Each member was loaded in a ramp (pseudo-static) manner, and then a static load was maintained. Three levels of constant load were used and termed as low, medium, and high (L, M, and H). The low, medium, and high load levels were defined as 2.13 kN, 2.81 kN, and 3.12 kN, respectively. These values equate to approximately 100%, 140%, and 155% of the tabulated reference static strength of the groups according to the LRFD Manual (1996). All tests were performed at approximately 23.9°C and 55% relative humidity.

Time-to-failure was taken as the time coinciding with a sudden large change in deflection. The constant load tests were terminated after a majority of the members of a group failed but prior to the failure of all members in the group. Test durations corresponded to 220 days, 33.9 days, and 4.65 days for the low, medium, and high groups, respectively. Each surviving specimen was ramp-loaded to failure at loading rate of 21.35 N per min for the low level and 26.68 N per min for the medium and high load levels.

### *Gerhards: In-grade lumber*

Gerhards (1988, 2000) conducted ramp and step-constant load tests on the parent popula-

TABLE 1. *Summary statistics of modulus of elasticity.*

| Group | Mean ($10^3$ MPa) | COV (%) | Minimum ($10^6$ psi) | Maximum ($10^6$ psi) |
|---|---|---|---|---|
| | | Edge-Knot | | |
| 1B | 11.4 | 13 | 8.7 | 14.7 |
| 2B | 11.4 | 13 | 8.8 | 14.7 |
| 4B | 11.4 | 14 | 8.4 | 14.7 |
| 9B | 11.4 | 14 | 8.5 | 15.0 |
| | | In-Grade | | |
| 113 | 9.0 | 19 | 5.3 | 12.4 |
| 115 | 9.1 | 20 | 5.9 | 13.5 |
| 122 | 9.1 | 20 | 5.4 | 13.2 |
| 124 | 9.0 | 19 | 5.8 | 12.2 |

tion of the in-grade material. The in-grade material was selected such that each specimen would contain a grade-controlling defect (e.g., knot size and type and slope of grain) in the central 762 mm of the length. The material was graded Select Structural (SS), No. 1, No. 2, or No. 3. The members were 2 by 4s (38 mm by 89 mm), 2.44 m in length.

The modulus of elasticity of each board was determined using edgewise bending with a support span of 2.13 m. Two load points spaced 0.61 m apart were centrally located on the support span. All material was nondestructively evaluated, and groups of twenty-five boards each were formed among the four grades such that each group of a given grade had similar distributions of modulus of elasticity and strength ratios.

The specimens were tested using both ramp loads, step-constant, and constant loads. The configuration for each test was the same as that used to determine the modulus of elasticity. The ramp-loading rates were termed fast, medium, and slow, and the step-constant and constant loading levels were identified as high, medium, and low. The step-constant loading is of primary interest for the present study.

All uploading to the various step-constant levels was performed at a rate of 1.33 kN/min. The step-constant load histories were conducted again using prescribed loads based on the static strength distribution from similar groups of in-grade material. Specifically, four load levels were used and identified as low, medium, high, and very high (L, M, H, and VH). These loads equate to approximately 100%, 130%, 170%, and 225% of the tabulated reference static strength of the groups from the LRFD Manual (1996). The low, medium, and high levels also were used later in work done by Fridley et al. (1992a, b, c) on similar groups of in-grade material subjected to various environmental conditions and sequences. Gerhards' (1988) tests were performed at a constant 22.8°C with 50% relative humidity.

## EXPERIMENTAL PROGRAM

### *Material*

As mentioned, the lumber used in this study is part of a population of material that has been used in various research efforts, and all material had been previously nondestructively tested and sorted based on material properties into ‘‘like’’ groups. The edge-knot material available for the present study was 2 by 4 lumber determined to be No. 2 grade based on regrading and nondestructive evaluation. For the in-grade material, only No. 3 grade groups were available for this study. Table 1 summarizes the modulus of elasticity of the eight groups used in this study. Groups are identified in Table 1 by their original designations per Gerhards and Link (1987) and Gerhards (1988). All material was stored in a constant 22.8°C, 50% relative humidity environment prior to testing. Testing was conducted over relatively short periods of time (less than 50 min) in a heated, but otherwise uncontrolled, laboratory environment. Typically, the temperature during the test was approximately 20 to 25°C, and the moisture content ranged from approximately 9 to 12%.

### *Experimental setup*

A loading system consisting of a 99 kN actuator with controller, a data acquisition system, and a reaction frame was used to test the material under both the dynamic and static loading. Figure 1 is a photograph of the experimental set-up. End supports were each equipped with 2 steel angles back-to-back in

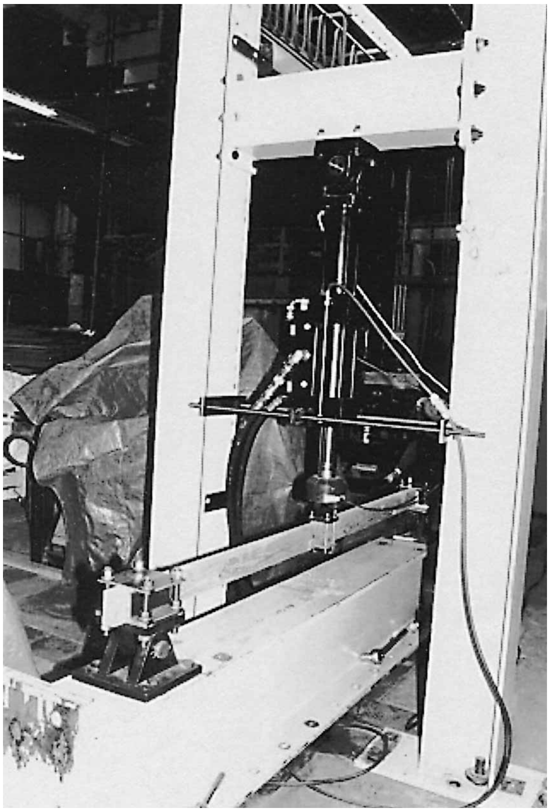

FIG. 1. Test set-up.

a book-end fashion to provide lateral support. A specimen was then placed between the steel angles, and a top plate was bolted on top in order to accommodate reversed loading. Rollers were placed between the specimen and the top and bottom plates, and the supports were allowed to pivot, and they provided what was assumed to be a pin- and roller-type support. Both load and displacement data were recorded. A load cell placed on the end of the actuator was used to measure load, and a linear variable displacement transducer (LVDT), internal to the actuator, was used to measure the displacements.

## *Loading protocol*

Seven of the eight groups of lumber were cyclically loaded in flexure under a sinusoidal load. The eighth group was subjected to static loading only. A sinusoidal model was used to represent both seismic and wind events. Following the cyclic loading, each surviving member was statically loaded to failure.

*Dynamic loading.*—Sinusoidal loading used in this research with the general form of the sinusoidal load is given as follows:

$$S(t) = S_{mean} + A \sin(\omega t) \qquad (1)$$

where $S(t)$ is the cyclic load, $t$ is the time, $S_{mean}$ is the mean load, $A$ is the half-amplitude of the cyclic load, and $\omega$ is the frequency of loading. This loading model allowed for both full reversals of load as well as nonreversed loading, depending on the value of $S_{mean}$. For the full reversal loading, $S_{mean} = 0$, meaning the maximum positive and maximum negative load were equal in magnitude to $A$. The nonreversal loading is defined by $S_{mean} = A$. Therefore, the maximum positive load is $2A$, and the maximum negative (or minimum) load is zero. As a practical matter, $S_{mean}$ was set slightly greater than $A$ (less than 5%) since using zero load as a control value is problematic given potential inertial forces in the test system.

For both the edge-knot and in-grade material, load levels were adapted from previous research projects (Gerhards and Link 1987; Gerhards 1988). For the edge-knot material, each specimen was dynamically loaded using three different load levels: low, medium, and high (L, M, and H). These load levels equate to the fifth percentile, eighteenth percentile, and twenty-fifth percentile values of the static strength distribution. In terms of design strength, these values are approximately 100%, 140%, and 155% of the tabulated reference static strength of the groups according to LRFD Manual (1996). The in-grade material was loaded through four different levels: very low, low, medium, high (VL, L, M, and H). These load levels equate to the third percentile, fifth percentile, fifteenth percentile, and fortieth percentile values of the static strength distribution. In terms of design values, these loads equate to approximately 80%, 100%, 130%, and 170% of the tabulated reference static strength of the groups from the LRFD Manual (1996). Note that the ''very low'' load level was not used by Gerhards (1988).

TABLE 2. *Experimental loading patterns.*

| Original group | Sample size | Loading frequency | Load reversal | Load level & sequence[b] | Experimental identifier |
|---|---|---|---|---|---|
| | | | Edge-Knot | | |
| 1B | 50 | 2.0 Hz | Full Reversal | L, M, H | EK-2.0-FR-LMH |
| 2B | 49[a] | 2.0 Hz | No Reversal | L, M, H | EK-2.0-NR-LMH |
| 4B | 50 | 2.0 Hz | No Reversal | H, M, L | EK-2.0-NR-HML |
| 9B | 50 | 0.2 Hz | No Reversal | L, M, H | EK-0.2-NR-LMH |
| | | | In-Grade | | |
| 113 | 25 | 0.2 Hz | Full Reversal | M, VL, L, H | IG-0.2-FR-MVLLH |
| 115 | 25 | 0.2 Hz | Full Reversal | VL, L, M, H | IG-0.2-FR-VLLMH |
| 122 | 25 | — | — | Ramp | IG-Ramp |
| 124 | 25 | 2.0 Hz | Full Reversal | VL, L, M, H | IG-2.0-FR-VLLMH |

[a] One member of group 2B was not included due to damage incurred during shipping.
[b] VL = very low; L = low; M = medium; and H = high load level.

In both previous studies (Gerhards and Link 1987; Gerhards 1988), the load was applied at two points, symmetrically located about the centerline of the member, whereas in this study, only a centrally located single point load was used. The single point load was necessitated to avoid the introduction of inertial forces (caused by accelerating the mass of the spreader beam and load head required for two-point loading) during the dynamic tests. Thus, load levels were determined for this study that produced equivalent maximum bending moment and elastic stress as were produced in the corresponding static load tests performed by Gerhards and Link (1987) and Gerhards (1988). For example, in Gerhards and Link (1987), a ‘‘low’’ load corresponded to a sustained load of 2.13 N, whereas in this study, a ‘‘low’’ load corresponded to a peak load of 1.56 N. As a result, both loads produced equivalent maximum moment and bending stress in the member. This difference in loading obviously produces different distribution of moment along the length of the test beams (i.e., moment diagrams), and this difference also can affect behavior. Thus, one group of in-grade material (Group 122) was tested in a ramp-load (pseudo-static) manner so as to assess the effect of loading on behavior.

For the cyclic loading, each load level was loaded for a total of 100 cycles at either 0.2 Hz or 2.0 Hz, depending on the particular group, or until failure if failure should occur. Potentially then, for the edge-knot material, each member was subjected to a total of 300 cycles, and for the in-grade material, each member was subjected to a total of 400 cycles. Each set of 100 cycles at a prescribed load level is then considered a load stage. Table 2 outlines the loading sequence for each group of both the edge-knot and in-grade materials. Note that for the edge-knot material, the grade-controlling edge knot was placed such that it was on the tension side for the non-reversed loading. Also in Table 2, an experimental group identifier is established to allow intuitive identification of test parameters for each group. For example, per Table 2, EK-2.0-NR-HML defines an edge-knot group tested under a 2.0 Hz non-reversed high, medium, low loading sequence (i.e., Group 4B).

*Static loading.*—Static loading was performed on the one group of in-grade material (Group 122; IG-Ramp) and for all members surviving the dynamic loading. The purpose for statically loading one group of material was used to establish the magnitude of the difference of loading methods (i.e., central-point versus two-point loading) on the apparent moment capacity (strength) of the lumber. The purpose of the static tests on surviving member was to determine the residual strength of the boards. To be consistent with the research performed by Gerhards (1988), a ramp-load to failure of 1.33 kN/min was used.

TABLE 3. *Summary statistics of moisture content.*

| Group | Experimental identifier | Mean (%) | COV (%) | Minimum (%) | Maximum (%) |
|---|---|---|---|---|---|
| | | Edge-Knot | | | |
| 1B | EK-2.0-FR-LMH | 10.9 | 3 | 10.2 | 11.7 |
| 2B | EK-2.0-NR-LMH | 10.2 | 4 | 8.7 | 10.7 |
| 4B | EK-2.0-NR-HML | 10.7 | 3 | 9.6 | 11.4 |
| 9B | EK-0.2-NR-LMH | 10.3 | 4 | 9.3 | 11.0 |
| | | In-Grade | | | |
| 113 | IG-0.2-FR-MVLLH | 10.8 | 4 | 10.0 | 11.5 |
| 115 | IG-0.2-FR-VLLMH | 10.9 | 5 | 9.2 | 11.9 |
| 122 | IG-Ramp | 10.7 | 4 | 10.1 | 11.6 |
| 124 | IG-2.0-FR-VLLMH | 10.6 | 4 | 9.8 | 11.4 |

### *Moisture content*

Immediately after a board failed, whether failure occurred during dynamic or static loading, a sample of wood was taken from an uncracked section near the failure region in order to determine the moisture content. The moisture content was determined for each sample on an oven-dry basis.

## RESULTS AND DISCUSSION

### *Moisture content*

Table 3 presents summary statistics of the groups' moisture content. The moisture content shown was obtained from oven-dried samples cut from each specimen immediately after failure. This includes both those members that failed during the dynamic loading and those loaded to failure during the post-cyclic static loading. A comparison with Gerhards and Link (1987) and Gerhards (1988) indicates similar moisture content ranges for both series of tests.

### *Failure definition*

Defining failure was accomplished two ways. For the first approach, "Type I" failure was defined as a member that failed by breaking into two, or more, pieces, which resulted in a complete loss of load-carrying capacity during the cyclic portion of the experimental testing process. In the second approach, "Type II" failure was defined as a loss in the ability to maintain the prescribed load, even though the member may not have been physically or visually damaged and may have retained some level of load-carrying capacity. Common to Type II was failure in one direction (i.e., either positive or negative bending moment) with full or partial capacity remaining in the other direction.

Failures were expected during the dynamic loading segment of the experimental testing even though an analysis using available damage models and the loads for testing indicated failure would not occur. This assumption was based on the previous related research by Gerhards and Link (1987) and Gerhards (1988). In their studies, failures (Type I) occurred during the ramp load to maintained static load (Gerhards and Link 1987) and ramp and step-constant loads. Both of these load scenarios are similar to the dynamic loading used in this research. Gerhards and Link (1987) and Gerhards (1988) defined failure as the complete loss of any ability to carry any type of stress (Type I failure).

Both Type I and II failures were observed with the edge-knot members; however, no Type I and relatively few Type II failures were observed with the in-grade material. The assumed reason for this difference in the numbers of failures is the stress concentration and local cracking resulting from the presence of the imposed edge knots. Type I failures in the edge-knot material tended to be catastrophic and sudden, while Type II tended to be more gradual and progressive.

TABLE 4. *Summary of Type I failures of edge-knot material (no Type I failures observed for in-grade).*

| Group | Experimental identifier | Number of failures | | | |
|---|---|---|---|---|---|
| | | First stage | Second stage | Third stage | Total |
| 1B | EK-2.0-FR-LMH | 0 | 3 | 1 | 4/50 |
| 2B | EK-2.0-NR-LMH | 1 | 2 | 3 | 6/49 |
| 4B | EK-2.0-NR-HML | 9 | 0 | 0 | 9/50 |
| 9B | EK-0.2-NR-LMH | 0 | 2 | 7 | 9/50 |

### *Dynamic behavior*

*Type I failures.*—Since under dynamic loading only the edge-knot groups experienced Type I failures, this is the only material discussed in this section. A summary of the number of failures for each edge-knot group is given in Table 4. The failure data from Table 4 are also plotted in Fig. 2. Note that the lines connecting the data points are used to aid in identifying trends, not to imply interpolated values between stages. Group 1B (EK-2.0-FR-LMH) exhibited the lowest number of Type I failures of all four groups, and this was the only group of the four tested with a full-reversed loading. This may indicate that full-reversed loading is not as damaging to the specimens as non-reversed or "single-sided" loading. However, this reduction in number of failures may be more likely the result of the specimens not experiencing the same cumulative duration of loading as groups tested under a non-reversed loading sequence. Groups 1B, 2B, and 4B (EK-2.0-FR-LMH, EK-2.0-NR-LMH, and EK-2.0-NR-HML), were all cycled at 2.0 Hz; however, Groups 2B and 4B (EK-2.0-NR-LMH and EK-2.0-NR-HML) show a higher number of failures than Group 1B (EK-2.0-FR-LMH). In addition to this, Group 1B (EK-2.0-FR-LMH) had no specimens fail during

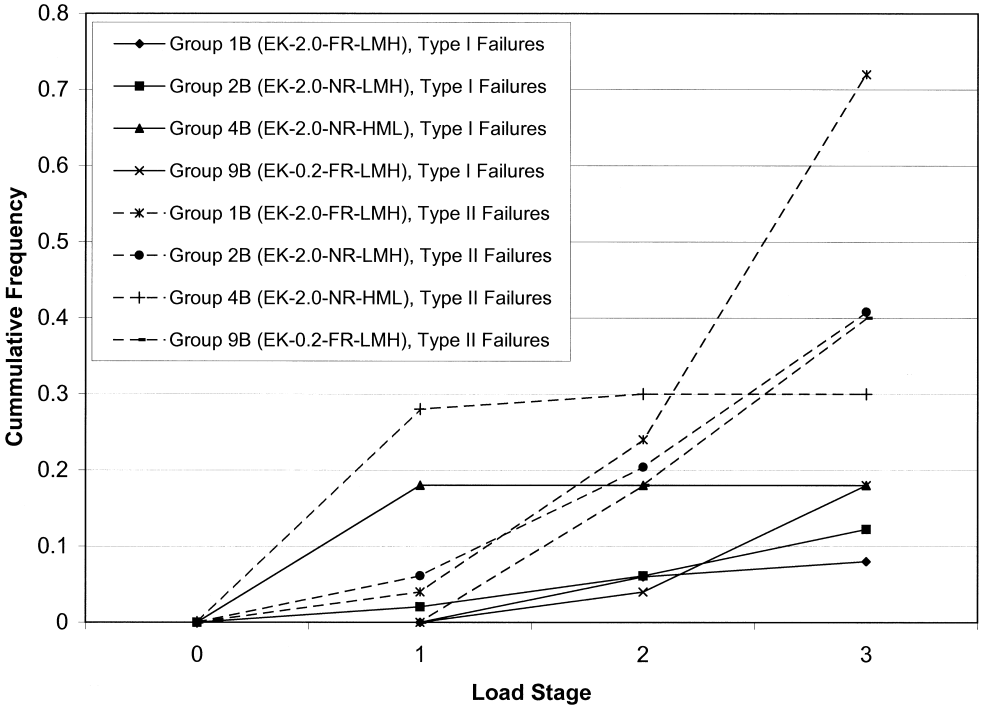


FIG. 2. Cumulative frequency comparison of Type I and Type II failures (edge-knot material only).

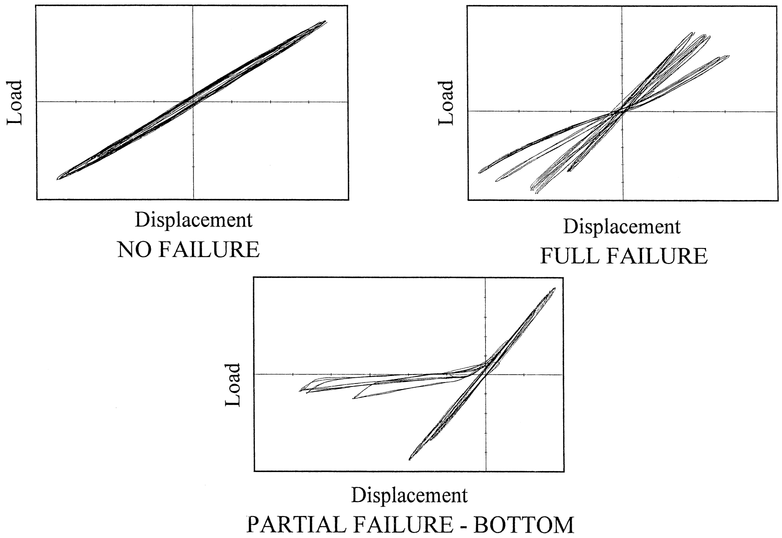


FIG. 3. Load-deflection plots of typical Type II failures.

the first loading cycle. Group 9B (EK-0.2-NR-LMH) was the only group cycled at 0.2 Hz and, even though it was tested with a non-reversed loading and the same loading sequence (i.e., L, M, H) as Group 2B (EK-2.0-NR-LMH), it had the highest number of failures. This, again, is likely attributable to the cumulative duration of load acting on the member. Since each member in each group of the edge-knot material was cycled for 300 cycles, a frequency of 0.2 Hz will cause the member to be under load for ten times as long as those with a frequency of 2.0 Hz. This observation would be consistent with the concept of cumulative damage and creep-rupture phenomenon.

Groups 2B and 4B (EK-2.0-NR-LMH and EK-2.0-NR-HML) were both loaded at 2.0 Hz with a non-reversed load. The difference was in the sequencing of the load: Group 2B was loaded low, medium, and then high (L, M, H) while Group 4B was loaded high, medium, and then low (H, M, L). The number of failures for Group 4B is 1-½ times greater than that of Group 2B; thus load sequencing, or history, was observed to have an effect on strength. Loading the members with the low load first may tend to relax the wood fibers prior to higher loading levels, thus yielding fewer failures during the high loading event. This may be, in part, supported through an energy-based definition of failure (Fridley et al. 1992c). All failures for Group 4B (EK-2.0-NR-HML) occurred within the first 25 cycles (12.5 s) during the high period of loading, and no failures occurred after that. These failures tended to be sudden and catastrophic, while the failures of Group 2B (EK-2.0-NR-LMH) tended to be more gradual and progressive.

*Type II failures.*—As noted in the previous section, many members of each group survived the cyclic portion of testing. By survived, it is meant that specimens did not physically break into two, or more, pieces during testing; however, many members did experience partial failures. An alternate and more conservative definition of failure is then initiation of failure, or occurrence of a partial failure, rather than the total collapse of the member. This is best accomplished by examining the hysteresis curves of the specimens and is similar in approach to what was used by Fridley et al. (1992c) for static loading. Figure 3 illustrates three "modes of failures" that were observed for Type II. Partial failures can result from both visible as well as micro-level cracking, and may occur on the top, bot-

TABLE 5. *Classification of Type II failures.*[a]

| Group | Experimental identifier | Number of partial failures: Bottom only | Top only | Top & bottom | Total |
|---|---|---|---|---|---|
| | | Edge Knot | | | |
| 1B | EK-2.0-FR-LMH | 9/50 | 3/50 | 24/50 | 36/50 |
| 2B | EK-2.0-NR-LMH | 4/49 | 0/49 | 16/49 | 20/49 |
| 4B | EK-2.0-NR-HML | 0/50 | 0/50 | 15/50 | 15/50 |
| 9B | EK-0.2-NR-LMH | 10/50 | 0/50 | 10/50 | 20/50 |
| | | In-Grade | | | |
| 113 | IG-0.2-FR-MVLLH | 4/25 | 0/25 | 2/25 | 6/25 |
| 115 | IG-0.2-FR-VLLMH | 3/25 | 1/25 | 1/25 | 5/25 |
| 124 | IG-2.0-FR-VLLMH | 0/25 | 2/25 | 0/25 | 2/25 |

[a] By definition, Type II includes all Type I failures. Type I failures are included as ''Top and Bottom'' failures.

tom, or both top and bottom of the member. Additionally, by definition, Type II failure includes Type I failures and is inherently a more conservative definition of failure. Table 5 summarizes the number of partial failures by their mode. Table 6 summarizes the number of Type II failures experienced by each edge-knot and in-grade group with respect to the stage of loading. Based on the conservative nature of the Type II failure definition, the number of failures is greatly increased (c.f., Table 4 for edge-knot material). This can best be visualized by referring to Fig. 2 where the observed cumulative frequencies for Type I and Type II failures are plotted for the edge-knot material. Figure 4 is a plot of the cumulative frequencies for Type II failures for both the edge-knot and in-grade material. Note that the lines connecting the data points in Fig. 4 are used to aid in identifying trends, not to imply interpolated values between stages.

The number of failures for each group using the Type II definition of failure resulted in drastically different results than using the Type I failure definition. Groups 1B, 2B, and 4B (EK-2.0-FR-LMH, EK-2.0-NR-LMH, and EK-2.0-NR-HML) were all cycled at 2.0 Hz; however, unlike when the definition of a Type I failure is used, Group 1B (EK-2.0-FR-LMH) showed the highest number of failures. This was also the only one of the three groups (1B, 2B, 4B) to have been tested under a full reversal of the loading. Group 9B (EK-0.2-NR-LMH) was the only group cycled at 0.2 Hz. However, the number of failures produced in this group using the Type II definition of failure falls in the middle of the other three groups. Groups 2B and 9B (EK-2.0-NR-LMH and EK-0.2-NR-LMH) had identical loading patterns, including non-reversal of the load, the only difference being the loading frequency. Group 2B (EK-2.0-NR-LMH) with a LMH sequence and Group 4B (EK-2.0-NR-HML) with a HML sequence, were both loaded at the

TABLE 6. *Summary of Type II failures.*

| Group | Experimental identifier | Number of failures: First stage | Second stage | Third stage | Fourth stage | Total |
|---|---|---|---|---|---|---|
| 1B | EK-2.0-FR-LMH | 2 | 10 | 24 | N/A | 36/50 |
| 2B | EK-2.0-NR-LMH | 3 | 7 | 10 | N/A | 20/49 |
| 4B | EK-2.0-NR-HML | 14 | 1 | 0 | N/A | 15/50 |
| 9B | EK-0.2-NR-LMH | 0 | 9 | 11 | N/A | 20/50 |
| 113 | IG-0.2-FR-MVLLH | 1 | 0 | 0 | 5 | 6/25 |
| 115 | IG-0.2-FR-VLLMH | 0 | 0 | 0 | 5 | 5/25 |
| 124 | IG-2.0-FR-VLLMH | 0 | 0 | 0 | 2 | 2/25 |

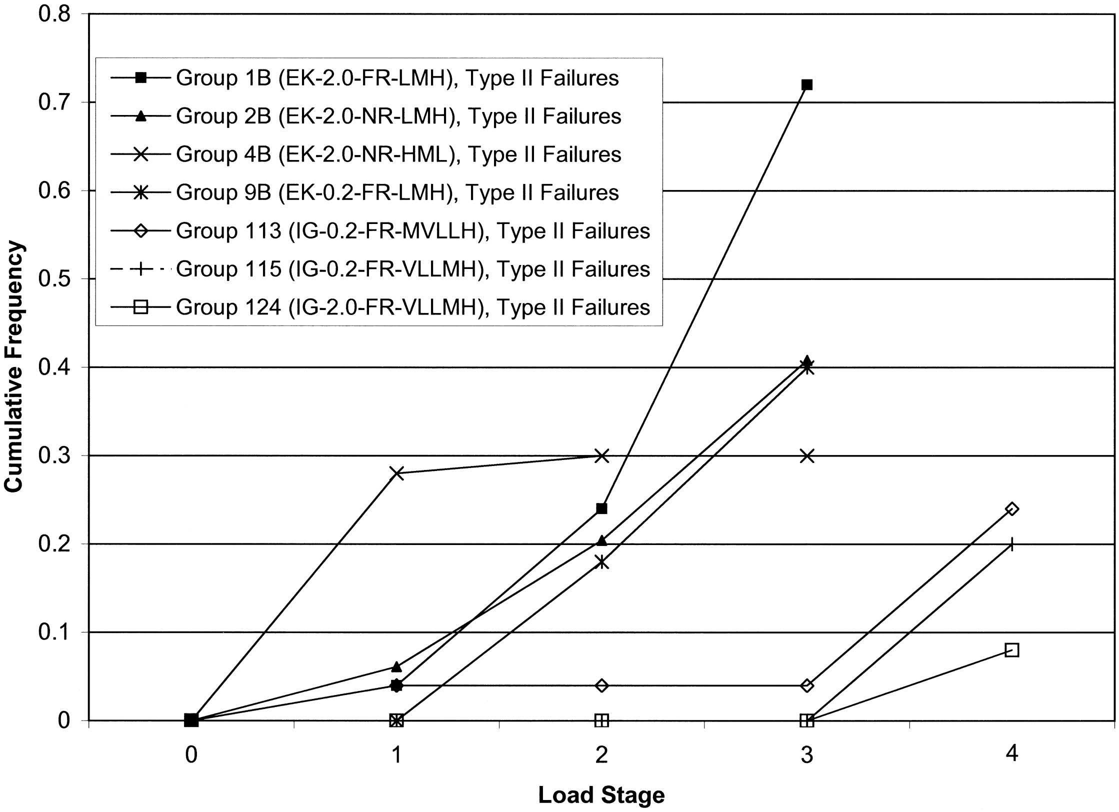


FIG. 4. Cumulative frequency of Type II failures (edge-knot and in-grade materials).

same non-reversed rate of 2.0 Hz. Contrary to the results using the Type I failure, Group 4B had a lower number of failures than Group 2B when using the Type II failure definition. In fact, Group 4B has the lowest number of failures of all of the 4 groups. Also, it seems that either a board in this group (4B) experiences complete failure (top and bottom) or no failure at all when using the Type II failure criteria.

Considering the in-grade material, it is noted from Table 6 and Fig. 4 that the two groups tested at 0.2 Hz (i.e., Group 113, IG-0.2-FR-MVLLH, and Group 115, IG-0.2-FR-VLLMH) but exhibited a greater number of failures than the group tested at 2.0 Hz (i.e., Group 124, IG-2.0-FR-VLLMH). In fact, the only difference between Group 115 (IG-0.2-FR-VLLMH) and Group 124 (IG-2.0-FR-VLLMH) was the frequency of loading (0.2 Hz versus 2.0 Hz); yet the failure rate was significantly greater at the lower frequency. This, again, is likely attributable to the cumulative duration of load acting on the member. Since each member in each group was cycled for up to 400 cycles (100 cycles at each load stage), a frequency of 0.2 Hz will cause the member to be under load for ten times as long as those with a frequency of 2.0 Hz. As stated previously, this observation would be consistent with the concept of cumulative damage and creep-rupture phenomenon.

One other observation from the in-grade material echoes the observation from the edge-knot material that load sequencing, or history, has an effect on strength. Comparing the load sequencing and failures of Group 113 (IG-0.2-FR-MVLLH) and Group 115 (IG-0.2-FR-VLLMH), it is noted that the results are quite similar with one additional failure reported for Group 115 than Group 113. It is observed that

TABLE 7. *Static and residual strength of in-grade material.*

| Group | Experimental identifier | Sample size | Mean ult. strength (MPa) | COV (%) |
|---|---|---|---|---|
| 113 | IG-0.2-FR-MVLLH | 19 | 24.0 | 20 |
| 115 | IG-0.2-FR-VLLMH | 20 | 25.9 | 15 |
| 122 | IG-Ramp | 25 | 21.7 | 15 |
| 124 | IG-2.0-FR-VLLMH | 23 | 27.4 | 19 |

the one additional failure in Group 115 occurred during the ''medium'' load stage, which was designated for that group to be the load level for the first load stage; all other failures of both groups occurred during the final stage at the high load level. While this is only one failure and thus lacks any statistical support, it supports the concept that loading the members with lower loads first may tend to relax the wood fibers prior to higher loading levels, thus yielding fewer failures during the high loading event. Again, this concept may be, in part, supported through an energy-based definition of failure (Fridley et al. 1992c).

### *Residual strength*

To assess the residual effects of the dynamic cyclic loading, the residual strength of all samples tested was evaluated. However, because of the relatively low number of undamaged edge-knot members (i.e., those members not classified as experiencing a Type II failure), only the results of the in-grade material tests are reported here. Additionally, only those members clearly surviving the dynamic loading (i.e., not experiencing a Type II failure) are included in the results.

Table 7 summarizes the mean and coefficient of variation (COV) of the ultimate strength of each group of in-grade material. The mean ultimate static strength of all groups, was greater than the mean strength determined by Gerhards (1988) for the same material. This is due to the difference in loading set-ups (i.e., mid-span vs. two-point loading). Considering the moment diagram for each test-up and recognizing that the majority of the failures did not occur at the centerline, but rather between the centerline and the supports, this difference can be explained and the magnitude of the difference is reasonable. The lowest mean is associated with group 122 (IG-Ramp), which was ramp-loaded only. The reason for this is assumed to be that the lower strength members of the dynamically loaded groups failed during the dynamic load. Statistically, the four populations of strength data are not significantly different. Therefore, it is concluded that the dynamic load history imposed on the three in-grade groups did not result in reduced ultimate static strengths.

## SUMMARY AND CONCLUSIONS

Two definitions of failure were developed in this study. Type I failure defined failure as occurring when a member physically broke into two, or more, distinct pieces. Type II failure defined failure as the occurrence of a partial failure or partial loss of load-carrying capacity. As far as the preferred definition of failure is concerned, Type I results were consistent with current theory regarding cumulative damage and failure of wood, yet the Type II definition appears to be a more reasonable definition for failure for the purposes of this study. Members do not necessarily need to break into distinct pieces to be considered failed. If a member is designed to carry a specific load and it does not carry that load, then it can be considered to be a failed member. In several instances, the required load was carried, but a significant increase in deflection was noted. In many applications, such large increases in deflection would not be acceptable. Furthermore, the Type II failure is more conservative than the Type I failure.

The mean ultimate static failure strength tended to be slightly greater than that of the previous related research endeavors (Gerhards and Link 1987; Gerhards 1988). This can be explained by the differences in the test set-ups. To allow higher cyclic frequencies, this study used a single loading point at mid-span, while the previous studies used a two-point loading system. With this in mind, the residual ultimate static strength (in-grade) did not seem adversely affected by the dynamic loading. Members of either material group (edge-knot or in-grade) tended to fail only at load levels well above their tabulated reference strength as defined by the LRFD Manual (1996). Overall, 1 out of 274 (0.36%) experienced a Type I failure and 6 out of 274 (2.2%) experienced a Type II failure (which includes the Type I failure) at or below the tabulated reference strength (per the LRFD Manual (1996)). Given this, the duration of load factors in the NDS and the LRFD appear reasonable. Specifically, the load duration factor, $C_D$, of 1.6 in the NDS (2001) and the time effect factor, $\lambda$, of 1.0 in the LRFD (1996) are reasonable and acceptable due to the results of the static ultimate strengths and the conservatism of the models from which these factors are derived.

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