EFFECT OF 85 YEARS OF SERVICE ON MECHANICAL PROPERTIES OF TIMBER ROOF MEMBERS. PART III. RELIABILITY STUDY

Kenneth J. Fridley

Associate Professor
Department of Civil and Environmental Engineering
Washington State University
Pullman, WA 99164-2910

Michael O. Hunt

Professor and Director

and

John F. Senft

Associate Professor Emeritus

Wood Research Laboratory
Purdue University
West Lafayette, IN 47907-1200

(Received October 1995)

ABSTRACT

The first two parts of this series (Fridley et al. 1996a, b) presented a comprehensive experimental and analytical duration of load (DOL) study of Purdue University's Peirce Hall, an 85-year-old, turn-of-the-century building razed in 1989. In this part of the research, we approach the structure from a probabilistic standpoint. We treat the material properties and loading as random variables in order to answer the following questions: Would we have ever seen any DOL effects in Peirce Hall? If not, and recognizing that the structure was in general conformance with current design practice, are we overly conservative in current design considering DOL? If yes, how often, and how does this relate to the level of safety we currently assume in design? We found that Peirce Hall, with randomness of loading and material properties, had a finite probability of experiencing a DOL failure, but not as high as assumed in current design. That is, the probability of Peirce Hall experiencing a DOL failure was less than what would be predicted using current DOL-analysis procedures. The major reason for this lower probability of failure is not due to an "over-designed" Peirce Hall, but is contributed to differences in real loading and assumed loading. Specifically, the snow load process assumed in current DOL-analysis procedures utilizes a rectangular representation of snow events, when a triangular representation is more appropriate. The rectangular event produces greater damage and higher probabilities of failure than the triangular event.

Keywords: Duration of load, damage accumulation, reliability, stochastic load, wood structures.

INTRODUCTION

The first two parts of this series (Fridley et al. 1996a, b) presented a comprehensive duration of load (DOL) study of Purdue University's Peirce Hall, an 85-year-old, turn-of-the-century building razed in 1989. In part I (Fridley et al. 1996a), we tested material salvaged from the roof system of the building following procedures compatible with those used around the turn-of-the-century to determine the post-service mechanical properties of the timbers. Comparing the post-service properties to estimated original properties led to the conclusion that the structure suffered no residual DOL effect from the 85-year service. In part

II (Fridley et al. 1996b), we analytically evaluated the structure for DOL effects to determine whether current theory would predict similar results as the experimental program. The structure was found to be in general conformance with current design requirements (i.e., AF&PA 1991). Further, the loads experienced by the structure, with snow load being of primary importance, were in general agreement to loads assumed in current design (i.e., ASCE 1993). Using the five most popular DOL models, all of which are based on the idea of damage accumulation under sustained loads leading to failure, we found no significant DOL effect analytically, which agreed with the experimental conclusion. Some of the models predicted very small amounts of damage, while others predicted no damage whatsoever; however, the amount of damage predicted by any of the models was insufficient to affect strength.

In this part of the research, we approached the structure from a probabilistic standpoint. Rather than assuming we knew explicitly the properties of the materials and the loads, as was done in parts I and II, we now treat the material properties and loading as random variables. In this manner, we essentially "build" Peirce Hall thousands of times and simulate what we did in parts I and II. That is, we answer the following questions: Would we have ever seen any DOL effects in Peirce Hall? If not, and recognizing that the structure was in general conformance with current design practice, are we overly conservative in current design considering DOL? If yes, how often, and how does this relate to the level of safety we currently assume in design?

STOCHASTIC LOAD MODELING

The first step in a reliability analysis is to define the loads, or more specifically in the case of a duration of load reliability analysis, the load processes. In this study, we consider two types of loads: dead (self-weight) and snow. The effects of wind are not considered as a significant loading, but are considered to affect the snow load pattern (i.e., drifting) on the roof (see Fridley et al. 1996b). This section presents the loading assumed in the reliability analysis, including the formulation of a stochastic snow load model derived from local weather data.

Dead load

The self-weight of a structure is typically well defined, but the total dead load is assumed to be underestimated by a small amount due to uncertainties in other dead load components such as permanent equipment, partitions, roofing, etc. The magnitude of the dead load follows a normal distribution with a mean value 5% over the nominal design value, or $D = 1.05D_n$, and coefficient of variation (COV) of 0.10. In design, dead load estimates are based on the minimum design loads for materials as specified in load standards (e.g., ASCE 1993). For reliability analysis of this type, a ratio of the nominal design snow load to the nominal design dead load (S_n/D_n) is assumed. Previous parametric studies (e.g., Ellingwood and Rosowsky 1991; Philpot et al. 1992, 1995; Rosowsky and Ellingwood 1990) have shown the reliability to be relatively insensitive to the S_n/D_n ratio in the range of 3 to 5 and suggest the use of $S_n/D_n = 4$, which is adopted herein. Since the dead load is assumed constant, it is modeled as a single pulse acting throughout the life of the structure.

Snow load

Currently, snow load processes are evaluated using simple load pulse models. One model in particular, used by Ellingwood and Rosowsky (1991) in a duration of load reliability study, represents snow events as rectangular load pulses of random magnitude, with a fixed duration of two weeks. The general load model is a Bernoulli pulse process in which the load pulse is either "on" or "off", no overlapping of events is allowed, and the magnitude of the event is constant throughout its duration. This form of snow load modeling may not truly represent the loading patterns experienced in nature but is believed to be a conservative approach. Fridley and Rosowsky (1994), however, illustrated the extreme sensitivity of the duration of load (i.e., damage accumulation) process to the shape of the load pulse. Therefore, for the purposes of this study, a snow load process model is developed from local climatological data and used in a reliability analysis. The developed snow load model is compared to the Bernoulli model (Ellingwood and Rosowsky 1991) in terms of the model itself and associated reliabilities.

Bernoulli Rectangular Load Pulse Model.—A rectangular load pulse model was presented by Ellingwood and Rosowsky (1991) wherein the distribution of the individual event magnitudes is related to the distribution of yearly maximums. The general form of the distribution relation is as follows:

$$F_{max}(x) = [(1 - p_n) + p_n F_i(x)]^n \qquad (1)$$

where p_n = the probability that the model is on, n = the number of events possible during a single season, F_i = the event distribution, and F_{max} = the distribution of yearly maximums. The distribution of yearly maximums is assumed to be lognormal. The model parameters have been defined by the evaluation of weather stations in several locations in the northeast quadrant of the United States, and the snow season was determined to be 182 days. For general locations, the probability that the event is on, p_n, is defined to be 0.20, and the number of events per season, n, is defined as 13. The distribution parameters for the determination of the magnitude of the event are dependent on the values given in the ASCE ground snow load map (ASCE 1993). The average snow event is defined as $0.20S_n$, where S_n is the nominal design snow load (50-year MRI), and is assumed to have a coefficient of variation of 0.87.

Triangular model development.—The snow loads used in the formulation of the stochastic load pulse model were developed from 86 years of weather data obtained from the Midwest Cooperative Weather Service (Fridley et al. 1994). The patterns of water-equivalent snow depth were investigated on a day-by-day basis in order to determine what load pulse shape best described the natural events experienced. The data were divided into individual snow events, defined as consecutive days with snow on the ground. Each event was then evaluated to determine what pattern (pulse shape) the snow followed.

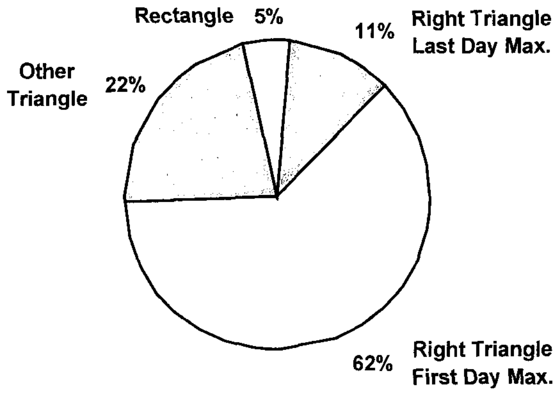

FIG. 1. Distribution of snow event shapes.

Two sets of events were selected for evaluation. The first consisted of events that resulted from only one snowfall. An event was determined to contain only one snowfall if it contained only one increase in snow depth. Each of these single events was evaluated as a whole. The second group consisted of events that were the result of multiple snowfalls, as indicated by the number of increases in snow depth. Each of these multiple events was broken up into the component events, and each of the components was evaluated separately.

Four distinct patterns were identified: the rectangular shape used in the Bernoulli model and three different triangular patterns, with the maximum magnitude on the first or second day, the last day, or some day in the middle of the event. Figure 1 shows the distribution found among the events. The triangular form with the maximum occurring on the first or second day was by far the most common, with approximately 62% of the events taking this shape. The rectangular Bernoulli pulse was the least common, occurring in only 5% of the events. Due to this finding, a triangular load

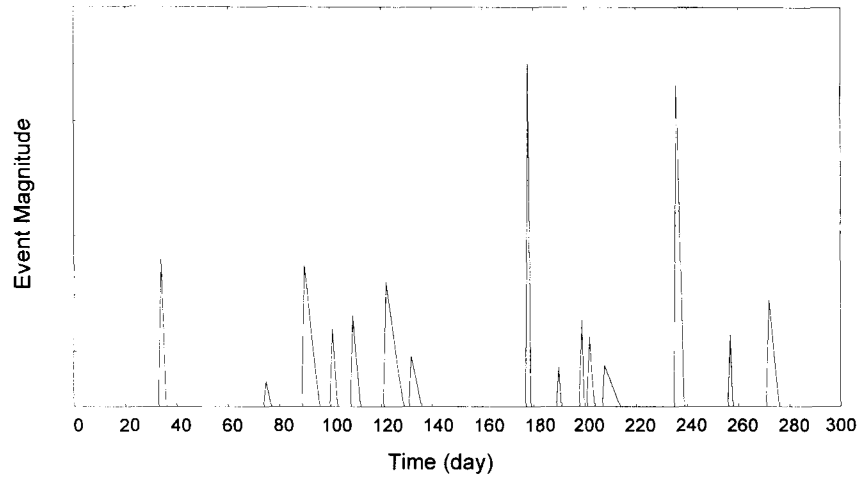

FIG. 2. Predicted snow loads using the Triangular Load Pulse Process.

pulse model, which experienced the maximum load on the first day of the event and decreased linearly to zero throughout the rest of the event duration, was developed.

Yearly snow seasons were evaluated, and it was determined that a 150-day period would best represent the length of the snow season. In this season, the probability that a snow event occurs was determined to be 0.25. The event magnitudes were determined to follow a lognormal distribution, the duration of events to follow an exponential, and the length of time between events to follow a lognormal distribution. The length of time between events is defined as the number of days between the onset of consecutive events.

To confirm the accuracy of the developed snow process model, the 50-year MRI snow load suggested by the process was compared to the 50-year MRI load suggested by the data (Fridley et al. 1994) as well as established snow load maps (ASCE 1993). The current design snow load for the West Lafayette area is 958 Pa (ASCE 1993), while the load data indicate the 50-year MRI load to be 1,000 Pa (Fridley et al. 1994). The triangular model was found to produce 50-year design loads very similar to those actually experienced.

The model prepares a load history where the load pulse is at its maximum on the first day and decreases linearly on a daily basis, and the possibility of overlapping events is allowed. Figure 2 is a graphical presentation of two snow seasons of random snow events generated using the developed triangular load pulse process. By comparison, Fig. 3 is a graphical presentation of two snow seasons of a Bernoulli rectangular representation of the same data (i.e., the Bernoulli process has the same probability of maximum load and occurrence as the triangular process). As seen in these two plots, the triangular load process is significantly more sparse than the Bernoulli process, with maximum loads occurring for shorter duration.

STATIC STRENGTH OF THE MATERIAL

The strength distributions used in each analysis were obtained from the In-Grade testing program (Green and Evans 1987). The material strength followed a Weibull distribution for nominal 2 by 10 (51-mm × 254-mm) No. 2 southern pine members. The Weibull Shape Parameter was given as 3.57 and the Weibull Scale Parameter was 6,580. These parameters provided a computed mean strength of 36.7 MPa (5,330 psi) and a coefficient of variation of 0.42. This is very similar to the strength estimated by adjusting the small clear value

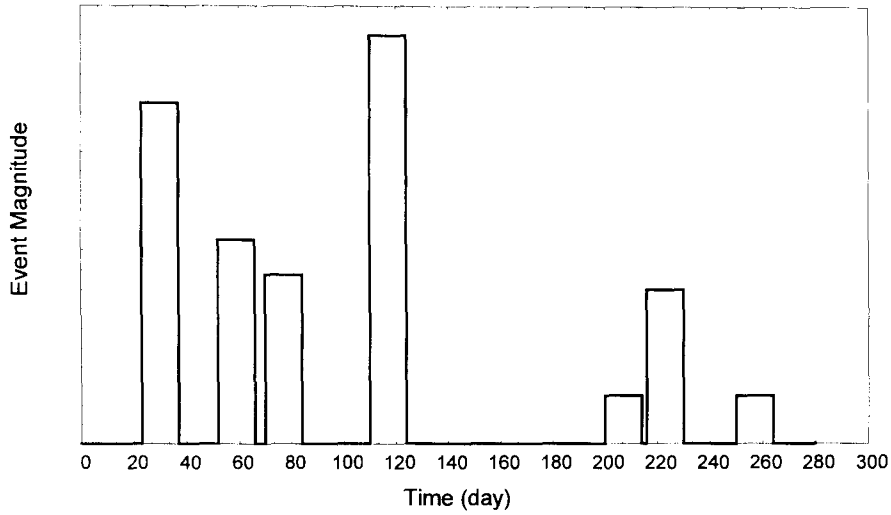

FIG. 3. Predicted snow loads using the Rectangular Load Pulse Process.

determined for the Peirce Hall roof timbers (Fridley et al. 1996a) per ASTM D 245 (ASTM 1991).

DURATION OF THE LOAD (DAMAGE) MODEL

In order to simulate duration of load effects, an appropriate duration of load model must be selected. Several types of duration of load models are available, including damage accumulation models (the most prevalent), energy models, empirical models, etc. For this study, Gerhards' Exponential Damage Rate Model (Gerhards 1979, 1988) was chosen since (1) Ellingwood and Rosowsky (1991) used this model extensively in their development of DOL factors for Load and Resistance Factor Design and, more importantly, (2) it is computationally quite efficient. Given the number of simulations conducted for this study, efficiency was a concern.

Gerhards' damage model is given as follows:

$$d\alpha/dt = \exp(-A + B\sigma) \qquad (2)$$

in which α = damage state variable defined for the range zero to one where zero implies no damage (virgin state) and unity defines failure, σ = applied stress ratio defined as the ratio of applied stress (load) to the static strength (ultimate load), and A and B are model constants. In this study, the values $A = 40.0$ ln(day) and $B = 49.7$ are assumed (Fridley et al. 1996b).

RELIABILITY ANALYSIS

As is typical in the United States, a 50-year design life was assumed for the reliability analysis, meaning the duration of load response was evaluated over simulated 50-year periods. As is also typical, reliability is defined in terms of the reliability index, β, where the relationship between β and the probability of failure is given by:

$$\beta = \Phi^{-1}(1 - P_f) \qquad (3)$$

where P_f = the probability of failure, which is equal to the number of failures observed in simulation divided by the total number of simulations, and Φ^{-1} = inverse standard normal probability density function.

To determine whether a failure has occurred during a particular simulation, a limit state equation must be written. Typically, the limit state equation is written in the following general form:

$$g(\boldsymbol{x}) = g(x_1, x_2, \ldots, x_n) = 0 \qquad (4)$$

in which $\boldsymbol{x}$ = the vector of all variables affecting failure (i.e., loads, material properties, dimensions, etc.). By convention, the limit state function g($\boldsymbol{x}$) is formulated such that $g < 0$ indicates failure, $g > 0$ is safe, and $g = 0$ is the failure surface.

Three general limit states were accounted for in this reliability study: (1) overload failure, (2) critical load pulse failure, and (3) duration of load failure. Overload failures result from the application of a stress value equal to or in excess of the short-term static strength of the material and have the following limit state equation:

$$g(\sigma) = 1 - \sigma \tag{5}$$

where σ = the applied stress ratio.

A critical pulse failure occurs when the damage resulting from a single event is large enough to induce failure, regardless of any previously accumulated damage in the material. This form of a duration of load failure was presented by Rosowsky and Fridley (1992), and the associated limit state equation for a critical pulse failure is:

$$g(\alpha_E) = 1 - \alpha_E \tag{6}$$

where α_E = the amount of damage resulting exclusively from an individual load event.

Duration of load failures occur when the amount of calculated damage, α_T, over a series of loading events equals or exceeds unity. The limit state equation representing duration of load failures is as follows:

$$g(\alpha_T) = 1 - \alpha_T \tag{7}$$

By definition, when an overload failure occurs, a duration of load and critical pulse failure also occur. Similarly, a critical pulse failure implies that a duration of load failure also occurs. Duration of load failures, however, may occur independently. Therefore, it is expected that β_{OVLD} (overload reliability) is greater than β_{CP} (critical pulse reliability), and β_{CP} is greater than β_{DOL} (duration of load reliability).

The form of the general stress ratio equation used in Gerhards' damage model is as follows:

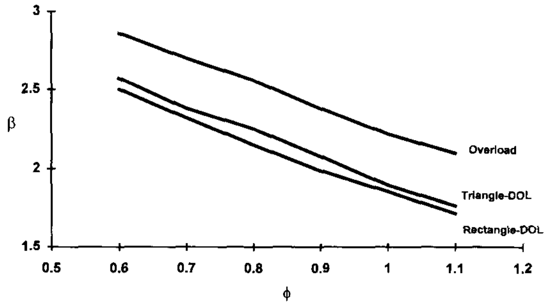

FIG. 4. β–ϕ curve for both snow load models.

$$\sigma(t) = \frac{D + S(t)}{1.2D_n + 1.6S_n} \frac{\phi}{(F_r/F_{.05})} \tag{8}$$

The equation includes the applied dead load, D, live snow load, $S(t)$, as well as nominal dead and snow loads, D_n and S_n. The resistance factor, ϕ, is the strength reduction factor for the material under analysis. The static strength and 5% exclusion strength for the members are given as F_r and $F_{.05}$, respectively.

The normalization of the stress ratio (Eq. 8) allows for an efficient computer-based Monte-Carlo reliability analysis. Three random variables are considered for each iteration in the analysis: dead load, D, snow load, S, and static strength, F_r. Each iteration represents 50 years; therefore, the snow load value changes multiple times during each iteration, and the dead load and static strength values change between iterations. Various ϕ-factors, ranging between 0.6 and 1.1, were assumed in the determination of reliability (β–ϕ) curves representing the two snow load models being investigated. In this analysis, 20,000 iterations were performed for each ϕ-factor.

RELIABILITY RESULTS

Overload failures occur when the applied stress is greater than the static strength. Duration of load failures result from a series of load pulses or a single critical load pulse. The reliabilities for both overload and DOL limit states considering both the triangular and rectangular load pulse process models were determined. Figure 4 compares the reliabilities resulting from overload, the triangular load pro-

TABLE 1. *Resistance factors and duration of load factors representing both snow load process models.*

Model	$\phi_{Overload}$	ϕ_{DOL}	λ
Triangular	0.9	0.7	0.78
Rectangular	0.9	0.66	0.73

cess, and rectangular load process. Note that the overload curves for the rectangular and triangular models coincide, as expected, since both models have equal extreme event distributions. From Fig. 4 it is apparent that the triangular load pulse model produced slightly higher reliability values when considering duration of load effects and snow loads.

This reliability analysis shows that the triangular model results in higher duration of load reliabilities than the rectangular model. The general form of the triangular load pulses more accurately represents the natural events being modeled and is, therefore, assumed to be a more accurate representation of the load history. This indicates that, in Peirce Hall, a duration of load failure (or at least some level of damage), although possible, was less likely than assumed in current design owing to the nature of the loading.

Duration of load factor comparison

If the triangular snow model were used in the development of Load and Resistance Factor Design duration of load factors, as the rectangular load pulse model has been, less duration of load reduction for snow loads would be implied for design. The load duration factor, λ, is the ratio of duration of load and overload ϕ-factors, ϕ_{DOL}/ϕ_{OVLD}, representing a constant reliability between overload and duration of load failures (Ellingwood and Rosowsky 1991). For each model, duration of load factors were calculated for an overload target reliability index of 2.3, equaling the approach of Ellingwood and Rosowsky (1991). Table 1 presents the data obtained from Fig. 4, used in the determination of the duration of load factors. The rectangular pulse process duration of load factor approximately equals the findings of Ellingwood and Rosowsky (1991). A larger duration of load factor (less reduction in design strength) represents the results from the triangular model evaluation. This difference is a result of the higher reliability associated with the triangular snow model.

Importance of critical load pulses

Each duration of load failure was investigated to determine if it was the result of accumulated damage or damage induced by one extreme event, or set of overlapping events. Results indicate that extreme events are responsible for over 99% of the duration of load failures observed. Extreme events are those with a magnitude large enough to produce failure in the member without considering the amount of previously accumulated damage. Some of these events may exceed a stress ratio of one (overload); therefore, the member fails without considering duration of load effects. The events that cause duration of load failure but do not reach overload show that it is not damage accumulation, but instead is damage associated with an extreme load pulse that leads to failure. If the duration of load reliabilities were calculated for Fig. 4 using only the concept of a critical pulse to define duration of load failures, the curves would fall essentially on top of the duration of load curve as presented.

Recognition that damage accumulation failures are almost exclusively the result of critical pulses may redefine the approach to damage accumulation analysis. Instead of investigating loads experienced throughout the service life of a structure, it might be more desirable to investigate the occurrence of critical events expected during the service life of the structure. This observation would imply that future investigations focus on short-term, high-stress testing rather than long-term, low-stress tests.

SUMMARY AND CONCLUSIONS

In the first two parts of this series (Fridley et al. 1996a, b), we presented a comprehensive experimental and analytical duration of load study of Purdue University's Peirce Hall, an 85-year-old, turn-of-the-century building razed in 1989. In this part of the research, we treated the material properties and loading at random variables in order to answer the following questions: Would we have ever seen any DOL effects in Peirce Hall? If not, and recognizing that the structure was in general conformance with current design practice, are we overly conservative in current design considering DOL? If yes, how often, and how does this relate to the level of safety we currently assume in design? We found that Peirce Hall, with randomness of loading and material properties, had a finite probability of experiencing a DOL failure, but not as high as assumed in current design. That is, the probability of Peirce Hall experiencing a DOL failure was less than what would be predicted using current DOL-analysis procedures. The major reason for this lower probability of failure is not due to an "over-designed" Peirce Hall (see Fridley et al. 1996a), but is contributed to differences in real loading and assumed loading. Specifically, the snow load process assumed in current DOL-analysis procedures utilizes a rectangular representation of snow events (Ellingwood and Rosowsky 1991), when a triangular representation is more appropriate. The rectangular event produces greater damage and higher probabilities of failure than the triangular event. This research indicates that we may be slightly more conservative in design considering snow DOL effects than currently assumed due to the assumed simple representations of real load processes.

ACKNOWLEDGMENTS

This paper is based on work supported by the National Science Foundation under Grant No. MSS-9296190. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors also acknowledge Mr. Michael Warden, Facilities Department, Purdue University, for providing plans and records related to Peirce Hall; Mr. Kenneth Scheeringa, Midwest Cooperative Weather Service, Purdue University, for providing the weather data for West Lafayette; Dr. Ronald L. Sack, School of Civil Engineering and Environmental Science, University of Oklahoma, for his help in the snow load analysis; Mr. J. Bryan Mitchell, formerly with the School of Civil Engineering and Environmental Science, University of Oklahoma, for writing much of the computer code used in the reliability analysis; and Ms. Kathy A. Roberts, School of Civil Engineering and Environmental Science, University of Oklahoma, for her help in managing the volumes of snow data used to develop the load model.

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