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Evolution of probabilistic analysis of timber structures from second-moment reliability methods to fragility analysis

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ABSTRACT

In the last 30 years, there have been significant advances made in the areas of probabilistic modeling of timber mechanical properties, structural analysis models for wood-frame structural systems, and stochastic modeling of structural and environmental loads. Collectively, this work has formed the scientific underpinning for modern limit-states timber design codes (e.g., in Europe, the United States, Canada, Japan, and elsewhere). Thus, it is fair to say that strength-based (limit states) design of structures in general, and timber structures in particular, is well developed and only incremental work is needed to keep these codes current. Advanced second-moment reliability techniques and numerical simulation techniques have been adequate for the development of today's probability-based limit states design codes, which are largely member-based with only a relatively simplistic treatment of multi-member systems. With increased attention being paid to economic loss as a limit state deserving of concurrent attention with life safety, especially following extremely costly natural disasters in the last two decades, there are efforts throughout the international engineering communities to move toward a philosophy of multi-objective performance-based (also called objective-based) design. This has required advanced modeling capabilities (e.g., of highly redundant structural systems of nonlinear materials), nonlinear and dynamic analysis capabilities, and often significantly more computational power. Coupled with these advances has been a move toward fragility analysis techniques to uncouple the hazard (e.g., seismic, wind) from the structural system response, thereby enabling more efficient probabilistic analysis and inference. Fragility techniques are also increasingly being accepted by those in the design communities (especially seismic design) and are likely to form the basis for next generation performance-based design procedures for all hazards. This paper describes this philosophical transition and reports on advances in fragility-based techniques that relate directly to the performance-based design of timber structures.

1. Introduction

The trend in structural design of timber (wood) structures worldwide has been toward probabilistic design, certainly in the last two decades. The US and Canada, two of the world's leading producers of structural timber and wood-based products and builders of wood-frame structures, developed their first generation of limit states design codes for timber in the late 1980s with first adoption by their respective codes and standards organizations in the 1990s. Much of the theoretical underpinning of the North American limit states codes for timber has been reported by Rosowsky, Ellingwood, Gromala and others (in the US) and by Foschi, Folz, and others in Canada. Indeed the simultaneous efforts between the US and Canada served to validate and support many of the findings/concepts promulgated by these new design limit states design philosophies for timber structures (e.g., load and resistance factor design or LRFD in the US, and limit states design in Canada).

Nearly 20 years have passed since these limit state codes were first adopted and it is fair to say that adoption by the design communities has been slow. This, of course, is not a reflection on the approach itself nor on its robustness or ease of use, but rather a reflection of an industry and designer base that is slow to change (i.e., "why change what isn't broken?"). Nonetheless, thoughtful and strategic decisions must be made about whether and how to continue promoting limit states design for wood structures in North America.

While limit states design for timber was adopted somewhat late in the game (e.g., relative to steel and concrete), its broad acceptance was delayed or at least further complicated by the emerging trend toward performance-based design (PBD), particularly for aseismic design. Thus, for example, as the wood community was struggling with how to treat wind and earthquake design issues (e.g., for shearwalls), new PBD procedures for shear structures were being promoted, largely developed on the west coast. The wood research community moved quickly to develop first-generation PBD concepts for seismic design of both low-rise and mid-rise wood buildings. Two high-profile multi-university/industry projects (the CUREE-Caltech

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Woodframe Project and the NEESWood Project) were conducted in the last 10 years. These projects were unique in that they both involved shake-table testing of full-scale timber buildings as "capstones" to extensive numerical modeling and analysis. As one task in the CUREE Project, reliability-based design tools were developed for shearwall design [1,2]. These design aids were reliability-based in that treatment of uncertainty in the seismic hazard was explicitly considered, and some consideration was given to treatment of the lesser uncertainties (e.g., in material properties). This study clearly identified the degree to which seismic hazard dominated the uncertainty and suggested essentially median-value based approaches for all other uncertain quantities. In effect, the CUREE project represented the bridge between traditional RBD approaches (e.g., calibration of partial safety factors for LRFD strength design equations) and fragility-based approaches. The subsequent NEESWood Project was entirely fragility-based. This transition is discussed in the present paper as are some of the issues considered (by the author) to be some of the challenges remaining both to researchers and code committees prior to widespread adoption of these next-generation probabilistic design procedures, whether strength-based or performance-based. The author's own work in these areas over the last 20 years forms the basis for the statements herein.

2. Limit states design (LRFD) for wood structures

2.1. Background: reliability-based design

Reliability-based (or limit states) design procedures for structural member design are well developed and, at this point, have been fully adopted/implemented as design practice in many countries. While differences exist among the different checking equation formats (e.g., load and resistance factor design in the US, partial safety factor design in the EU), they are quite similar in that they use combinations of factors on each of the load and resistance sides of the design equation. These factors account for uncertainty in the basic variables, consequence of failure, and so forth. Three different forms of checking equations are shown below:

US, load and resistance factor design (LRFD)

$$\phi R_n \geq \sum_i \gamma_i Q_{n_i} \tag{1}$$

National building code of Canada

$$\phi R_n \geq \gamma_D D_n + \psi\Big(\sum_i \gamma_i Q_{n_i}\Big) \tag{2}$$

General partial safety factor design (Eurocode)

$$\frac{R_n}{\gamma_{r_1}\gamma_{r_2}\gamma_{r_3}} \geq \gamma_{s_1}\gamma_{s_2}\gamma_{s_3}\left[fcn\left(\sum_i Q_{n_i}\right)\right] \tag{3}$$

Structural reliability can be evaluated by computing the probability that a particular limit state function is less than zero. The function is expressed for a particular limit state and a particular load combination. The failure probability can be expressed,

$$P_f = P[g(x_1,\ x_2,\ldots,\ x_n)] < 0 \tag{4}$$

where $g(\ )$ is the limit state function, and $x_1,\ldots,x_n$ are the basic variables (loads, strengths, geometric properties, etc.). The second-moment reliability index is related to the failure probability by $\beta = \Phi^{-1}(1-P_f)$ where $\Phi^{-1}(\ )$ = inverse of the standard normal distribution function. Early codes in the US were developed using simple first-order second-moment (FOSM) techniques. As theory evolved, advanced second-moment (i.e., FORM/SORM) techniques were employed to account for non-normal random variables, correlated variables, etc. Monte-carlo simulation (MCS) is used to evaluate limit state probabilities for problems which are too complex to be solved using FORM/SORM techniques.

In reliability-based (or limit states) design, explicit consideration is given to each relevant limit state (i.e., flexure, shear, deflection, etc.) in the design process. For each limit state considered, all relevant load combinations are checked to determine the controlling combination. Rules for load combinations as well as the bases for the selection of load and resistance factors (i.e., partial safety factors) are presented in the literature [3,4].

2.2. LRFD for wood structures

The US pre-standard efforts for LRFD for wood are documented in [5] while the comparable (and largely equivalent) Canadian efforts are documented in [6]. Some of the subsequent, and closely related, EU efforts are documented in [7,8]. These references summarize the both the philosophical bases for and the theoretical underpinning of each country or region's first generation limit states code for timber. This section summarizes some of the reliability studies that went into the development of the LRFD pre-standard and subsequent initial version of the LRFD for engineered wood construction in the US. The intent here is simply to reference some of the work completed along the way; the list is not intended to be complete.

The LRFD format and load combinations were taken from ASCE 7 [9] to be consistent with existing LRFD provisions for other structural materials (e.g., steel). The probabilistic background for these load combinations (and selected first-generation partial safety factors) is provided in [3]. The design strengths for wood members (different species, sizes, grades) were based on the extensive In-Grade Testing Program[1] [10], with some soft calibration modifications to assure alignment with the current NDS – the allowable stress design procedure with which design engineers had become very comfortable. Many of the reliability studies conducted subsequently made full use of the IGTP data, basing the statistical models for resistance on best-fit distributions and moments from the enormous data set. Ellingwood and Rosowsky [11] used time-dependent reliability analysis to evaluate a comprehensive set of load duration factors ("time effect" or "duration of load (DOL)" factors) considering different load combinations and statistics, material types (statistics on MOR), and proposed cumulative damage models, e.g., [12–14]. This work formed the basis for the time effect factors implemented in the LRFD standard and informed future thinking about comparable DOL factors (in the NDS). These results were also broadly validated by similar findings by the Canadians [6] (and later by studies conducted in the EU leading to their model code provisions for probabilistic design of timber structures [15,16]) using their species groups and loading statistics. The concept of cumulative damage in wood was examined for a number of years that followed with studies reported on damage accumulation in timber connections [17] and proposals for simplified cumulative damage analyses based on the concept of a single (or small number of) critical pulses [18]. Rosowsky and Ellingwood [19,20] coupled system reliability analysis and time-dependent reliability analysis techniques to examine time-dependent load-sharing in repetitive-member wood systems. The study looked at effects of system size (span, number of repetitive members), species and member size/grade effects, and different

[1] The In-Grade Test Program (IGTP) was conducted jointly by the United States and Canada to develop a statistical database of engineering properties for dimension lumber. The program was initiated after it was found that the properties of small clear wood specimens (which had been used to develop the design values for wood previously) were significantly different from those of full-scale ("in-grade") pieces of lumber. The IGTP thus provided the database of mechanical properties needed to develop the new probability-based design specifications. This ambitious program was conducted at a number of laboratories in North America over a period of seven years. All together, over 73,000 pieces of dimension lumber were tested and the results were published in an 8-volume set [10]. Information compiled in the IGTP included statistical moments and estimates of percentiles based on different distribution assumptions. Mechanical properties included MOR, MOE, tensile and compressive strengths. The data were adjusted to baseline conditions and presented by species, size, and moisture content.