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A reliability-based approach to uniform structural risk

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SUMMARY

The ASCE 7 loading standard recommends uniform risk loads to support reliability-based structural safety. Wind load risk is controlled by a fixed wind speed return period. The current provisions specify a unique return period for prescriptive Risk Categories that imply correspondence to reliability targets. However, this strategy fails to achieve uniform structural risk. A Monte Carlo reliability simulation demonstrates that design reliability fails to meet prescribed targets for typical design scenarios and fixed return periods. Furthermore, this investigation demonstrates that design reliability cannot be controlled by specifying fixed return periods. Consequently, the prescribed reliability targets are not achieved for all scenarios governed by the loading standard, resulting in non-uniform risk and inconsistent economy. Allowing the return period to vary as a function of target reliability is one approach that can achieve uniform risk. This reliability-based approach provides additional design flexibility, superior risk control, and improved economy.

Keywords: *Computational wind load evaluation, performance-based engineering, reliability, codes and standards*

1. INTRODUCTION

The North American ASCE 7 standard recommends uniform risk wind loads to support reliability-based structural safety. According to the standard, “A strength-level design wind speed map brings the wind loading approach in line with that used for seismic loads, in that they both are aimed at achieving uniform risk rather than uniform hazard, thus eliminating the use of a load factor for strength design.” (ASCE, 2022). The analytical justification for the codified wind speeds deserves scrutiny because these maps are critical for both structural safety and economy. Strength-level wind speed maps debuted in 2010 (ASCE, 2010). The original return periods were later confirmed by a reliability analysis (McAllister et al., 2018) for subsequent versions of the ASCE standard (2016, 2022). This study evaluates risk variation in the reliability analysis supporting fixed wind speed return periods and suggests improved procedures where they are warranted.

2. BACKGROUND

The ASCE 7-10 loading standard (ASCE, 2010) introduced ultimate wind speed maps for strength design. Previous versions of the standard provided wind speed maps for a 50-year return period that were used with importance factors to address risk, and a load factor to generate ultimate loads for strength design. Note that the 50-year period was selected for convenience, without technical justification (Ellingwood, 2000). The 2010 version of the standard also eliminated wind importance factors and introduced four Risk Categories (I-IV) to classify buildings and other structures. Three maps were produced corresponding to categories I, II, and a combined category III/IV. The ASCE 7-16 loading standard (ASCE, 2016) introduced a separate wind speed map for Risk Category IV structures. The new wind speed return period was determined by a Monte Carlo reliability simulation (MCRS) that was designed to confirm the wind speed return periods developed for ASCE 7-10 (McAllister et al., 2018). The original study supporting probability-based loading provisions (Ellingwood et al., 1980) considered multiple construction materials, multiple member types, and developed a set of load combinations valid for multiple design scenarios based on target reliability indices which were calibrated against existing practice. In contrast, McAllister et al. (2018) only considered one structural material (steel), one member type (compact, fully braced beam in bending), under the assumption that the true mean value of the directionality factor varies from the codified value, and only one load combination (Dead + Wind). Therefore, it's worth investigating if this unique configuration is representative of the wide variety of design scenarios governed by the loading standard.

3. METHODS AND RESULTS

This investigation includes a parametric study to quantify reliability variation for structures controlled by wind load effects and an analytic evaluation of the plotted results. For the numerical study, an MCRS was developed and calibrated to produce results identical to those reported by McAllister et al. (2018). For example, compare the Baseline data points plotted in Figure 1 to the results plotted in Figure 3 in McAllister et al. (2018) or the target reliabilities in ASCE 7, Table 1.3-1 (2022). The calibrated MCRS was used to compute reliability indices corresponding to each of the four fixed wind speed return periods. For each iteration, one variable changed, while all other parameters were held constant, identical to the baseline scenario values. Consequences for design reliability due to the codified return periods are demonstrated. A design approach that eliminates these consequences to achieve uniform risk is proposed.

3.1. Parametric Study

Four design scenarios were evaluated using the calibrated MCRS. One input varied from the baseline scenario in each iteration: structural material (reinforced concrete), member type (beam-column), mean value of the directionality factor (K_d = 0.85), and the load combination (Dead + Wind + Live, with a modest Live to Dead load ratio of 2:1). The MCRS parameter values are presented in Table 1. The MCRS returns a reliability index, β for each of the four prescriptive return periods. These four β values are plotted with trendlines in Figure 1. The resulting reliability indices varied over a large range and in all cases other than the baseline scenario, failed to meet the codified target values, β_o. Accordingly, the unique scenario considered by McAllister et al. (2018) is not conservative, is not broadly representative of common design scenarios, and does not satisfy the uniform risk criterion. Accordingly, the current ASCE 7 wind speed maps do not support uniform risk and have limited utility for the wide variety of design scenarios governed by the loading standard.

Table 1. Parameter Values and Legend

	Design Scenario									
	Baseline		R/C Beam		Steel Beam-Column		Directionality		Live Load	
Variable	Bias	COV	Bias	COV	Bias	COV	Bias	COV	Bias	COV
Resistance (R)	1.08	0.09	1.05	0.11	1.07	0.15	1.08	0.09	1.08	0.09
Dead Load (D)	1.05	0.10	1.05	0.10	1.05	0.10	1.05	0.10	1.05	0.10
Wind Load (W)	0.75	0.35	0.75	0.35	0.75	0.35	0.90	0.35	0.75	0.35
Live Load (L)	-	-	-	-	-	-	-	-	1.00	0.25
Load Combination	1.2D + W		1.2D + W		1.2D + W		1.2D + W		1.2D + W + 0.5L	
Mean Kd	0.71		0.71		0.71		0.85		0.71	

3.2. Analytical Study

The ASCE 7 loading standard implies that structural loads developed from a prescribed return period, T, will result in a design reliability index, β_{DSN}, equal to the target reliability index, β_o. For a range of design problems, the implication is that variance in β_{DSN} due to differences in material type, member type, etc. are acceptably small for the fixed value T, or that $\beta_{DSN} \approx \beta_o$ for all design scenarios subject to the loading standard provisions. However, this study demonstrates that generally $\beta_{DSN} \neq \beta_o$ for fixed wind speed return periods. Refer to Figure 1 and consider Risk Category II with a return period of 700 yrs, the range of design reliabilities for the small set of conditions considered in this study is $2.0 \leq \beta_{DSN} \leq 3.0$ compared to $\beta_o = 3.0$. The plotted scenarios demonstrate that when the return period is fixed, the reliability must vary as a function of each specific design scenario. This study demonstrates that fixed return periods cannot achieve uniform risk, even for small changes in the design scenario. To achieve uniform risk, a suggested improvement would permit the return period to vary as a function of the β_o. In this approach, wind speeds for different design scenarios will vary, but the corresponding β_o remains constant, thus satisfying the uniform risk criterion. Refer to Figure 1 and consider Risk Category II with a target reliability of 3.0, the range of return periods for the small set of conditions considered in this study is 700 yrs ≤ T ≤ 2,500 yrs. Note that the return period for a load combination including live load lies beyond the plotted range and is equal to 7,000 yrs. This result likely reflects a feature of the reliability model rather than objective reality, a point which should be noted and studied further. The reliability-based approach clearly results in uniform structural design risk in contrast to the varying risk associated with the fixed return period approach. According to the reliability-based approach, an MCRS returns T that guarantees β_{DSN} meets or exceeds any β_o for all members that pass the corresponding design check.

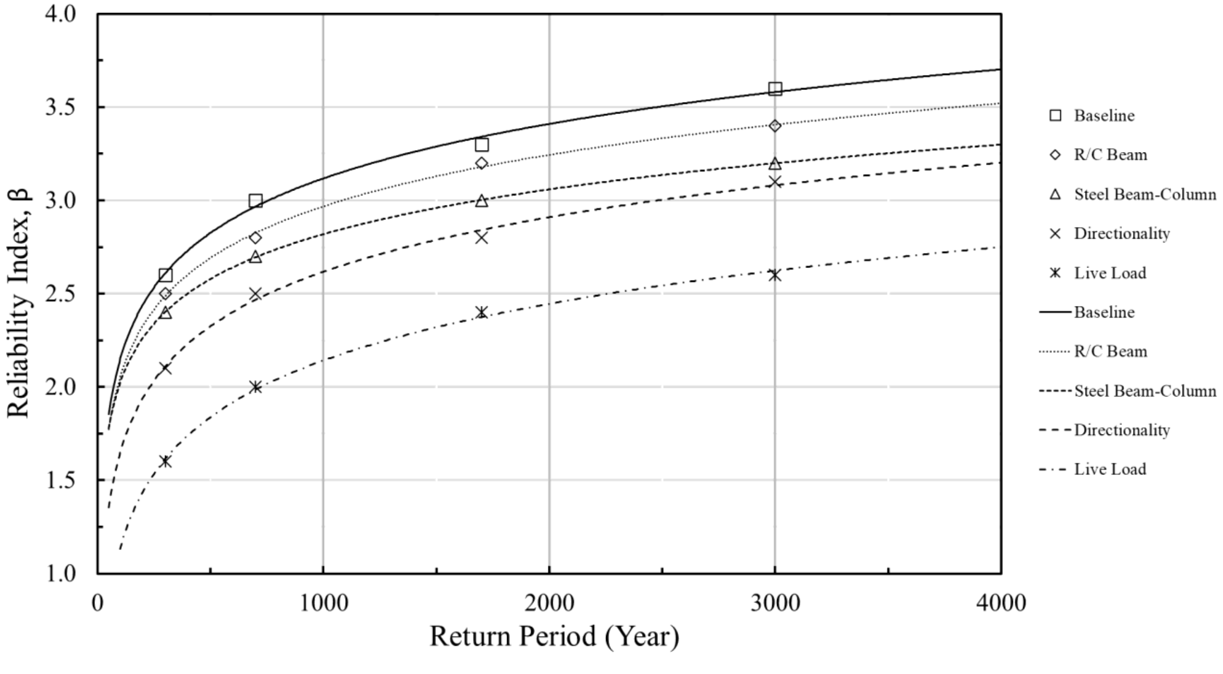

Figure 1: Reliability Index (β) vs. Return Period (yr)

4. DISCUSSION

This study demonstrates that significant risk variation is possible for typical design scenarios when the wind speed return period remains constant. Additionally, the current fixed wind speed return periods can not generally achieve the current reliability targets, a point that should be emphasized.

Accordingly, design risk is uncontrolled by the current prescriptive procedures. The apparent lack of main wind force resisting system failures due to design wind events indicates that the current wind speed return periods may be generally conservative. However, risk remains uncontrolled and conservative solutions are expensive, especially for structures sensitive to wind load effects. These are compelling reasons to seek an improved design procedure capable of providing positive risk control. Allowing the return period to vary as a function of the target reliability index ensures consistent design reliability for a wide range of design scenarios.

5. CONCLUSIONS

The current ASCE 7 return periods for ultimate wind speeds are based on procedures with inherent variability and limited analytical justification that result in non-uniform reliability. Furthermore, according to the standard (ASCE, 2010, 2016, 2022) prescriptive designs are "deemed to comply" with the prescribed reliability targets but are not required to demonstrate compliance, which is likely impossible anyway. The prescriptive wind speeds generally result in unnecessary waste due to overestimation or potential losses due to underestimation. The variation inherent to the prescriptive procedure vanishes when the basic wind speed is developed from a reliability analysis. This type of analysis can account for any construction material, member type, or load combinations of interest to structural engineers. Additionally, a reliability analysis can demonstrate compliance with standard reliability targets, an obvious advantage over the "deemed to comply" prescriptive provisions. Furthermore, reliability-based designs can be optimized for practically any scenario including design for alternative reliability targets and for any reference period, including the current arbitrary value. Project-specific data like material tests, wind tunnel studies, or wind speed records may also be incorporated into a reliability-based design for even greater accuracy. Finally, this approach is not limited to wind but can accommodate all hazards. Thus, not only is uniform risk between designs possible, but reliability-based design guarantees risk control for any design scenario, a significant advantage when compared to the non-uniform risk associated with the current prescriptive provisions.

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