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# Reliability assessment of reinforced concrete structures within the setting of performance-based wind engineering

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**SUMMARY:**
Performance-based wind engineering enables the possibility of designing wind-excited structural systems with controlled inelasticity at collapse prevention in contrast to traditional elastic design aimed at ensuring life safety. Key challenges that have emerged from this shift are related to the need to rapidly assess reliability for a wide range of inelastic limit states, including system collapse. To this end, a stochastic simulation framework that integrates a high-fidelity finite element modeling environment with a stochastic simulation scheme based on stratification is proposed for estimating failure probability/reliability over a full range of wind intensities and general uncertainties. In addition, the possibility of performing a wind multiple stripe analysis (MSA) for estimating failure probability/reliability was investigated. The proposed framework was illustrated on an archetype 45-story reinforced concrete building. The extreme efficiency of optimal stratified sampling was observed as was the capability of wind MSA to reduce the computational burden without any apparent loss of accuracy.

*Keywords: Performance-based wind engineering; Nonlinear dynamic analysis; Reliability analysis, MSA for wind*

## 1. INTRODUCTION

Core to maximizing the benefits of Performance-based wind engineering (PBWE) is the possibility of assessing the reliability of structural systems over a wide class of inelastic limit states, including collapse, while considering a full range of uncertainties in both the loading and model parameters (Arunachalam and Spence, 2022; Chuang and Spence, 2022, 2019). To this end, computational frameworks that enable rapid estimation of the reliability/probability of failure through the propagation of general uncertainties are essential. General stochastic simulation schemes for reliability assessment include direct Monte Carlo simulation as well as more efficient variance reduction techniques, including importance sampling (Jayaram and Baker, 2010) and stratified sampling (Arunachalam and Spence, 2023). However, while general, simulation-based methods can become computationally challenging due to the need for repeated nonlinear dynamic analyses over long time horizons (i.e., the one hour of typical nominal windstorms). To overcome this, in seismic engineering, conditional intensity measure ($IM$)-based approaches have been introduced with the aim of making inelastic performance assessments more practice-oriented and computationally affordable. These include incremental dynamic analysis (IDA) and multiple stripe analysis (MSA) (Baker, 2015). The goal of this paper is to first propose an efficient stochastic simulation framework that allows the propagation of general uncertainties in estimating the probability of failure of wind-excited reinforced concrete (RC) structures. The scheme minimizes the number of required dynamic nonlinear analyses through optimal stratified sampling. Secondly, the possibility of defining a MSA framework for wind is investigated as a means to further reduce computational effort in evaluating inelastic limit states in PBWE.

## 2. BACKGROUND ON THE SIMULATION SCHEMES

### 2.1. Optimal Stratified Sampling Scheme

Schemes based on optimal stratified sampling have recently been proposed to estimate small failure probabilities in wind engineering applications involving uncertain nonlinear dynamic systems with minimal model runs (Arunachalam and Spence, 2023). The approach is based on partitioning the sample space of the wind hazard into a number of mutually exclusive and collectively exhaustive events called strata. Direct Monte Carlo simulation is then adopted to estimate the conditional probability of failure in each stratum, and subsequently the total failure probability. The optimal sampling allocation is determined based on the results of a preliminary analysis that uses a limited sample set with equal allocation.

### 2.2. Multiple Stripe Analysis

General MSA estimates the distribution of an engineering demand parameter ($EDP$) from a series of performance assessments at different $IM$ levels (Baker, 2015). This process is generally computationally expensive due to the need to run a significant number of nonlinear dynamic analyses at each $IM$ level. To address this, Bradley (Bradley, 2013) suggested estimating the $EDP|IM$ relationship as a result of interpolation and extrapolation based on the response analyses at a few reference $IM$ levels. To estimate the small probabilities of failure associated with rare events, $IM$ levels at small exceedance rates are recommended as reference levels.

## 3. STOCHASTIC SIMULATION STRATEGY

To account for wind directionality in the stratified sampling scheme, a sector-by-sector approach is adopted based on dividing the wind direction into a number of sectors. The failure probability of the system, or of a limit state, is taken as the failure probability of the critical sector which can be estimated from a preliminary elastic dynamic response analysis carried out over all sectors. Once the critical sector is identified, the stratified sampling scheme with optimal sample allocation is adopted for propagating uncertainty through high-fidelity structural models developed in *OpenSees*. As illustrated in Fig. 1, uncertainty in the gravity loads, model parameters, and dynamic wind loads (through spectral proper orthogonal decomposition (POD) models (Suksuwan and Spence, 2019)) that are calibrated to building specific wind tunnel data) is included.

## 4. CASE STUDY

### 4.1. Building Description

The proposed stochastic simulation framework is illustrated on a 45-story archetype RC building loacted in New York City, as shown in Fig 2. Classified as a risk Category II structure, the target failure probability is $3.5 \times 10^{-5}$, and the associated reliability index, $\beta$, is 4.0 over a 50-year lifespan (American Society of Civil Engineers, 2022). A high-fidelity fiber-based structural is

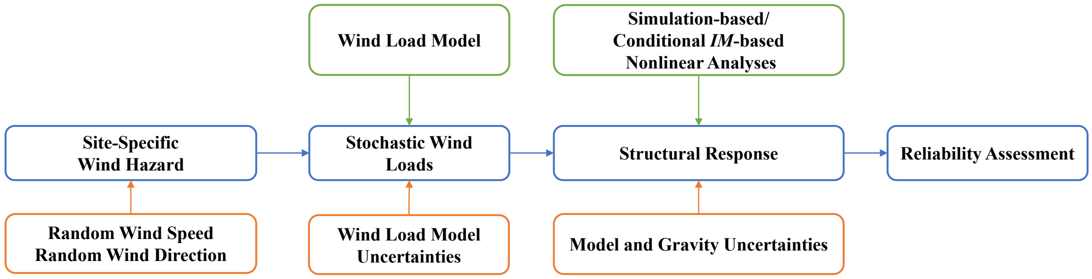


**Figure 1.** Flowchart of the reliability assessment scheme.

established in *OpenSees* to simulate the inelastic wind response. *Concrete02* and *SteelMPF* are adopted to simulate the stress-strain behavior of the concrete and reinforcing rebars. Fiber failure due to accumulation of damage and potential fracture of the rebar is modeled through the low-cycle fatigue (LCF) material wrapping the *SteelMPF*. Parameters defining the material models as well as the damping are modeled as random variables with probability distribution as outlined in Arunachalam and Spence, 2022. The site-specific wind hazard is defined at reference height over a 50-year lifespan by transfomring the 3 s gust wind speeds of the ASCE 7-22 wind maps. Given a wind speed, $v_H$, and direction, $\alpha$, a data-driven spectral POD model is adopted to generate realizations of the stochastic dynamic wind loads (Chuang and Spence, 2022).

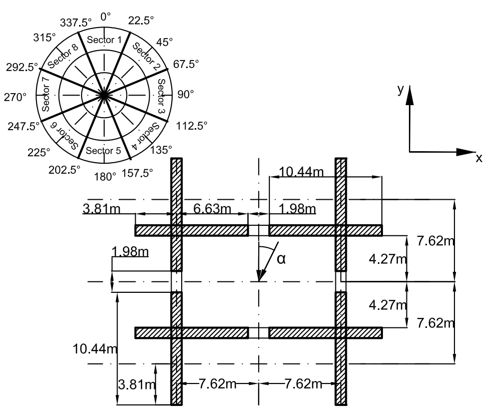


**Figure 2.** Building layout and wind direction sectors.

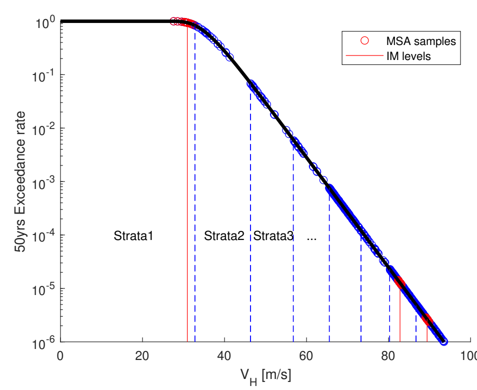


**Figure 3.** Random wind samples of the optimal stratified sampling scheme and three-level wind MSA.

## 4.2. Results

To estimate the probability of failure using the aforementioned stochastic simulation scheme, wind directions are equally divided into 8 sectors (i.e., Fig 2). The critical sector (i.e., sector 7) was determined from the distribution of elastic dynamic response base moment. Through partitioning the wind hazard curve into 8 strata, 541 samples were optimally allocated in the critical sector to estimate the reliability with respect to the limit states of interest. Subsequently, the median 20 samples in the $1^{st}$, $7^{th}$ and $8^{th}$ strata (for a total 60 samples) are utilized to perform a 3-stripe wind MSA with the mean wind speed of each stripe identifying the *IM* level. The wind speed samples of the stratified sampling scheme and MSA are plotted in Fig. 3. The probabilities of failure together with the reliability indexes over the lifespan with respect to limit states of interest are illustrated in Table 1. It can be observed that the optimal stratified sampling scheme is capable of estimating failure probabilities as small as $10^{-6}$ with only 541 samples. In addition, the proposed wind MSA only required 60 samples to estimate failure probabilities that are comparable to those of the stratified sampling. This example clearly shows the potential of both approaches.

**Table 1.** Failure probabilities/reliability indices for a 50-year lifespan

| LS | Description | Optimal Stratified Sampling | MSA with 3 *IM* levels |
|---|---|---|---|
| LS1 | System collapse | $5.92 \times 10^{-7}$ ($\beta$=4.86) | $1.34 \times 10^{-6}$ ($\beta$=4.69) |
| LS2 | X-direction Peak drift exceeding 1/50 | $9.87 \times 10^{-7}$ ($\beta$=4.76) | $1.36 \times 10^{-6}$ ($\beta$=4.69) |
| LS3 | Y-direction Peak drift exceeding 1/50 | $1.52 \times 10^{-5}$ ($\beta$=4.17) | $9.53 \times 10^{-6}$ ($\beta$=4.28) |
| LS4 | X-direction roof residual drift exceeding 1/1000 | $2.74 \times 10^{-5}$ ($\beta$=4.03) | $1.48 \times 10^{-5}$ ($\beta$=4.18) |
| LS5 | Y-direction roof residual drift exceeding 1/1000 | $5.44 \times 10^{-6}$ ($\beta$=4.40) | $8.73 \times 10^{-6}$ ($\beta$=4.30) |

## 5. CONCLUSIONS

In this paper, stochastic simulation frameworks are proposed for rapid reliability estimation of wind-excited structural systems by integrating a high-fidelity structural modeling environment with a stochastic simulation scheme based on optimal stratified sampling or wind MSA. To demonstrate the potential of the frameworks, a practical illustration was presented on an archetype 45-story RC building. The extreme efficiency of optimal stratified sampling was seen requiring roughly 500 samples in estimating failure probabilities in the order of $10^{-6}$. In addition, it is seen that wind MSA has the potential to reduce the number of required samples by an order of magnitude without any apparent loss of accuracy.


### ACKNOWLEDGEMENTS

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### REFERENCES


American Society of Civil Engineers, 2022. Minimum Design Loads and Associated Criteria for Buildings and Other Structures. American Society of Civil Engineers.

Arunachalam, S. and Spence, S. M. J., 2022. Reliability-Based Collapse Assessment of Wind-Excited Steel Structures within Performance-Based Wind Engineering. Journal of Structural Engineering 148, 04022132.

Arunachalam, S. and Spence, S. M. J., 2023. An efficient stratified sampling scheme for the simultaneous estimation of small failure probabilities in wind engineering applications. Structural Safety 101, 102310.

Baker, J. W., 2015. Efficient analytical fragility function fitting using dynamic structural analysis. Earthquake Spectra 31, 579–599.

Bradley, B. A., 2013. Practice-oriented estimation of the seismic demand hazard using ground motions at few intensity levels. Earthquake Engineering & Structural Dynamics 42, 2167–2185.

Chuang, W.-C. and Spence, S. M. J., 2022. A framework for the efficient reliability assessment of inelastic wind excited structures at dynamic shakedown. Earthquake Spectra 220, 104834.

— 2019. An efficient framework for the inelastic performance assessment of structural systems subject to stochastic wind loads. Engineering Structures 179, 92–105.

Jayaram, N. and Baker, J. W., 2010. Efficient sampling and data reduction techniques for probabilistic seismic lifeline risk assessment. Earthquake Engineering & Structural Dynamics 39, 1109–1131.

Suksuwan, A. and Spence, S. M. J., 2019. Performance-based design optimization of uncertain wind excited systems under system-level loss constraints. Structural Safety 80, 13–31.