

Robust Topology Optimization of High-Rise Building Facades under Stochastic Wind Loads

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SUMMARY

This paper presents a robust topology optimization framework for high-rise building facades subjected to stochastic wind loads. Uncertainties in turbulence intensity, wind field parameters, and material stiffness are modeled using Expansion Optimal Linear Estimation for spatially varying random fields and Stochastic Reduced Order Models for efficient uncertainty propagation. A multi-objective formulation minimizes the mean and variability of root mean square inter-story displacements and frequency weighted floor accelerations, improving both structural performance and occupant comfort. Reliability is enforced through probabilistic constraints on allowable inter-story drifts. The framework is further extended to include three-dimensional stochastic wind pressure fields obtained from computational fluid dynamics simulations, enabling optimization of bracing systems across all facades. Numerical results show that the proposed method significantly reduces response variability and failure probability compared with deterministic designs.

Keywords: *Robust topology optimization, Stochastic Reduced Order Models, Computational Fluid Dynamics*

1. INTRODUCTION

High-rise buildings are particularly sensitive to wind induced dynamic effects due to their height and flexibility, while the inherent variability of atmospheric winds introduces significant uncertainty in structural response. Excessive wind induced displacements and accelerations can adversely affect serviceability and occupant comfort, even when strength requirements are satisfied. Conventional design approaches typically rely on deterministic wind load representations, which do not explicitly account for response variability and may result in inefficient or overly conservative designs (Guest and Igusa, 2008).

Topology optimization has emerged as an effective tool for generating efficient structural layouts. However, most existing applications in building design remain deterministic and do not explicitly address uncertainties associated with wind loading and material properties. To address this limitation, this study proposes a robust topology optimization framework for high-rise building facades subjected to stochastic wind loads. The framework integrates efficient uncertainty quantification with a multi-objective robust formulation to minimize both the mean and variability of structural responses while enforcing reliability constraints. In addition, the approach is extended to incorporate three-dimensional wind pressure fields obtained from computational fluid dynamics simulations.

2. METHODS

2.1. Stochastic wind loading model

The wind loading acting on the building facade is modeled as a stochastic process composed of a mean wind component and a turbulent fluctuation. The mean wind speed variation with height is described using a logarithmic profile to account for surface roughness effects, while turbulent fluctuations are generated using spectral representation based on the Kaimal power spectral density and an exponential spatial coherence model. The resulting wind velocity time histories are converted into wind pressure time histories and subsequently transformed into equivalent nodal forces acting at each floor level of the facade.

2.2. Uncertainty representation and propagation

Multiple sources of uncertainty are considered, including turbulence intensity, wind field parameters, and material stiffness. Spatially varying uncertainties are modeled as Gaussian random fields and discretized using Expansion Optimal Linear Estimation (EOLE), which provides an efficient low dimensional representation while preserving spatial correlation. Non Gaussian uncertainties in wind parameters are represented through memoryless transformations of standard Gaussian variables (Bai et al., 2021). To enable efficient uncertainty propagation, Stochastic Reduced Order Models (SROMs) (Torres et al., 2021) are constructed to approximate the joint probability distribution of all uncertain variables using a small number of weighted samples, significantly reducing computational cost compared with conventional Monte Carlo simulation (MCS).

2.3. Robust topology optimization formulation

The objective of the robust topology optimization is to obtain facade designs that perform reliably under uncertainty by minimizing both the mean and the variability of a weighted performance measure that balances structural displacement mitigation and occupant comfort. The optimization problem is formulated as:

$$\begin{cases} \text{Find:} & \boldsymbol{\rho} \in \mathbb{R}^N \\ \text{Minimize:} & \bar{\mathcal{F}}(\boldsymbol{\rho}) = \mu(f') + \kappa \alpha(f') \\ \text{Subject to:} & V(\boldsymbol{\rho})/V_0 = V^* \\ & \mathbb{P}(\Delta_{\max} > \Delta_{allow}) \leq p_{lim} \end{cases} \quad (1)$$

where $\bar{\mathcal{F}}(\boldsymbol{\rho})$ is the robust objective function, $\mu(f')$ and $\alpha(f')$ denote the mean and standard deviation of the performance measure f' evaluated over the SROMs, κ is a user defined weighting factor controlling the emphasis on response variability, $\boldsymbol{\rho}$ is the element density vector with N design variables, $V(\boldsymbol{\rho})$ is the material volume, V_0 is the design domain volume, and V^* is the prescribed volume fraction. The probability constraint limits the exceedance of the allowable inter-story drift Δ_{allow} to a prescribed threshold (p_{lim}).

The multi-objective performance measure f' , evaluated from dynamic analysis using the HHT alpha scheme, is defined as

$$f' = w_d^{eff} \left(\frac{f_d}{f_{d0} + \epsilon_v} \right) + w_a^{eff} \left(\frac{f_a}{f_{a0} + \epsilon_v} \right) \quad (2)$$

Where f_d and f_a denote displacement based and frequency weighted acceleration-based response measures, respectively. The terms f_{d0} and f_{a0} are normalization factors, and ϵ_v is a small regularization constant. The weights w_d^{eff} and w_a^{eff} are used to dynamically balance the relative contribution of displacement and acceleration in the optimization.





3. RESULTS AND DISCUSSIONS

To evaluate the robustness of the optimized facade design, SROM based results are validated against an MCS. A total of 10 000 stochastic wind load realizations are applied to both the deterministic topology optimized design and the proposed robust design. Performance indicators include the mean and standard deviation of displacement and acceleration responses, the maximum inter-story drift, the probability of exceeding the allowable drift limit, and the relative improvement of the $\kappa=2$ robust design compared with the deterministic design under uniform wind loading.

Table 1 summarizes the MCS results. Compared with the deterministic design, the robust topology optimized facade exhibits reduced mean responses and significantly lower variability in both displacement and acceleration. The maximum inter-story drift is reduced, and the probability of exceedance is driven to near zero, whereas the deterministic design shows a non negligible failure probability. These results confirm the effectiveness of incorporating uncertainty directly into the optimization process.

The framework is further evaluated using three-dimensional wind pressure fields obtained from CFD simulations of a full-scale high-rise building. Time resolved facade pressures are converted into equivalent floor level nodal forces and represented using SROMs. Figure 1 shows the computational domain used for the CFD simulations and the resulting optimized facade topology obtained using CFD based stochastic wind loads.

Table 1: MCS validation of robust façade designs for different values of κ , compared with the deterministic design

	$\kappa=0$	$\kappa=1$	$\kappa=2$	Deterministic	Δ
$\mu(f_d)$	 15.4871	 15.3591	 15.3076	 16.6423	8.01%
$\alpha(f_d)$	7.5030	7.4403	7.4131	8.0795	8.25%
$\mu(f_a)$	1.5457	1.5438	1.5353	1.7490	12.22%
$\alpha(f_a)$	0.8258	0.8247	0.8200	0.9346	12.26%
g	0.0090	0.0083	0.0078	0.0121	35.54%
POE	0.10%	0.06%	0.00%	4.34%	100.00%

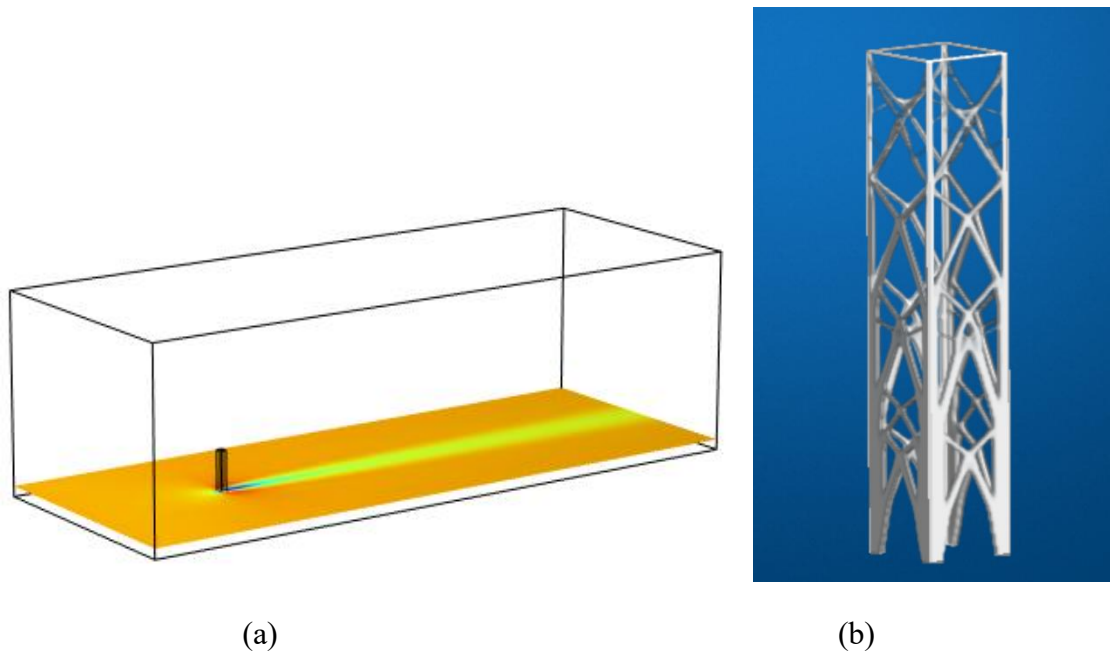


Figure 1: (a) Computational domain, (b) optimized facades.

4. CONCLUSIONS

A robust topology optimization framework for high-rise building facades subjected to stochastic wind loads has been presented. The method integrates SROMs with a multi-objective robust formulation to explicitly account for uncertainty in wind loading and structural properties. Monte Carlo validation demonstrates that the optimized designs achieve reduced response variability and near zero probability of exceeding allowable inter-story drift compared with deterministic solutions. The extension to three dimensional CFD derived wind pressure fields confirms the applicability of the framework under realistic wind conditions. The proposed approach provides an efficient and reliable tool for performance-based wind resistant design of high-rise building facades.

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