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Risk design optimization using many-objective evolutionary algorithm with application to performance-based wind engineering of tall buildings

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ABSTRACT

Risk design optimization (RDO) is a competent approach for automated performance-based structural design by achieving a balance between safety and economy. Performance-based wind engineering (PBWE) is aimed at improving the life-cycle functionality of wind-sensitive structures, hence could be the very field RDO is tailor-made for. In this paper, we embed PBWE of tall buildings into RDO and tackle some difficulties when integrating them directly. We first formulate an integrated stiffness and vibration control RDO problem, and employ a frequency domain closed-form solution for uncertainty quantification and uncertainty propagation through the excitation–response–performance chain. Then we reveal the multi-objective optimization nature of RDO, and circumvent the difficulties in serviceability loss estimation by replacing scalar total cost with high-dimensional objective vector. Micro multi-objective particle swarm optimization in conjunction with kernel-learning based principle component analysis is employed to solve the corresponding many-objective problem with multiple probabilistic constraints and discrete design variables. The optimization results of CAARC benchmark indicate that we simplify risk-based PBWE of tall buildings from a complex multi-objective decision making process into a relatively easy multi-attribute decision making process. Accordingly, convincing decisions can be made based on the explicit building performance rather than the unreliable loss information.

1. Introduction

Performance-based design (PBD) improves risk assessment by introducing convincing scientific techniques, which enable stakeholders to make informed decisions. Extensive applications reveal its trend towards mitigating short duration hazards (e.g., earthquake [1,2], gust [3] and fire [4]) and long term effects, such as corrosion [5] and fatigue [6]. Among them, wind hazard in itself consists of multi-level hazard events, which correspond to multiple performance requirements. Naturally, performance-based wind engineering (PBWE) framework [3] is modified for long-span bridges [7] and building structures [8–10]. However, there still exists ample room for its improvement and one of the foremost requirements is to equip PBWE with optimization techniques [11].

The development of optimal PBD is directly related with the state of the art of structural optimization techniques. Hence wind-resistant design optimization for tall buildings has experienced a rapid development last several years. Chan et al. improved the optimality criterion based stiffness optimization technique [12], and extended it to drift design [13] and habitability design [14,15] considering three-dimensional (3D) modes. Though these formulations were strictly derived, they cannot be expected to satisfy prescribed performance requirement. In the context of PBD, objective criteria are suggested to be described in a probabilistic manner, as the significance of any optimal solution would be relatively limited when the consideration of uncertainty is waived. Besides, to strictly enforce the performance objective, the target reliability should be set directly for the limit state [16] rather than the exceedance probability of mean wind recurrence interval [17].

Earlier contributions placed significance on the necessity to introduce probabilistic approaches in wind engineering [18–20]. Subsequently, great emphases were laid on the role of uncertainties in fundamental frequency and damping ratio for serviceability evaluation, because they may spread and shift the probability density function (PDF) of the resultant response [21–23]. The extent of the spreading would be amplified when multi-source uncertainties are arising through the excitation–response–performance chain. Reliability-based design optimization (RBDO) takes uncertainties into account and is under constraints related to the minimum

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target reliabilities specified by predefined performance requirements [24]. Applications of RBDO to structural design pose great challenge due to the large number of design variables and computational burden incurred from repeated reliability analyses. Approximate reliability method [25] and sampling-based method in conjunction with surrogate model [26–28] have been exploited to tackle these difficulties, and RBDO has shown competence on the design of wind-excited structure [29].

For the special issue on wind-resistant design of tall buildings, Spence et al. made original contributions by optimizing a tall steel frame under different fragility level [30,31], and extended the methodology into data-driven cases [32]. Huang et al. further improved the method in [13,15] by considering uncertainties in estimated wind speed and structural dynamic characteristics [33]. Though these RBDO approaches establish sound bases for automated PBWE of tall buildings, it has been empirically proved the optimality of RBDO solution fails when the structure would experience unavoidable damage in the future [34]. By striking a balance between safety and economy, risk design optimization (RDO) could be a competent alternative for PBWE of tall buildings. Its extensive applications to performance-based seismic design [35–37], an early attempt on mitigating hazard on wind-excited structure [38] and the formal propounding of risk-based PBWE methodology [7–10] indicate the possible benefit of integrating PBWE with RDO for tall building design. Owing to the uniqueness of tall building PBWE, existing probabilistic optimization approaches could be inappropriate to be directly extended into risk-based cases.

To bridge the gap between PBWE and RDO, PBWE of tall buildings is first formulated as an integrated stiffness and vibration control RDO problem in Section 2. Then we introduce 3D closed-form solution for uncertainty quantification and uncertainty propagation in Section 3. In Section 4, the original RDO problem is transformed into a many-objective RBDO problem. To solve this problem, we develop a constrained micro multi-objective particle swarm optimization (Micro-MOPSO) assisted with principle component analysis (PCA) in Section 5. Design optimization of a 45-story steel moment resisting frame example is performed in Section 6. Finally, we outline the conclusion of this paper in Section 7.

2. RDO formulation for serviceability PBWE of tall buildings

PBWE is originally proposed towards both ultimate limit state and serviceability limit state. Since wind-induced vibration may cause occupant discomfort, malfunction of facilities and excessive inter-story drift hence damage to non-structural elements (NSEs) [39,40]. Serviceability limit states play fundamental roles for tall buildings, especially the ones located in non-hurricane regions. All the failure consequences and the associated risks (expected loss) can be mitigated at the expense of introducing more initial safeties. From the structural design aspect, sizing optimization should be applied to all the structural elements for desired overall stiffness distribution. However, modifying the stiffness alone is low efficient to meet habitability performance requirement [14] as acceleration response is insensitive to the changes in structural frequencies and mode shapes. Hence we implement a smart tuned mass damper (STMD) at the top of the building to directly restraint the acceleration response. The RDO formulation for serviceability PBWE of tall buildings is formulated as

$$\underset{x}{\text{Minimize}}: \ C_T = w_1\left(C_U\sum_{i=1}^{L}(\rho_i l_i x_i) + C_D\right) + w_2\left(\sum_{j=1}^{N+1} p_j C_{1j}\right) + w_3\left(\sum_{k=1}^{2} p_k C_{2k} C_L\right) \tag{1}$$

$$\text{subject to}: \ p\left(\frac{U}{H} \geqslant \delta_{Top}\right) \leqslant p_D^T; \quad p\left(\frac{V}{H} \geqslant \delta_{Top}\right) \leqslant p_D^T; \quad p\left(\frac{\sqrt{U^2+V^2}}{H} \geqslant \delta_{Top}\right) \leqslant p_D^T \tag{2}$$

$$p\left[\frac{u_j - u_{j-1}}{h} \geqslant \delta_j\right] \leqslant p_j^T; \quad p\left[\frac{v_j - v_{j-1}}{h} \geqslant \delta_j\right] \leqslant p_j^T; \quad p\left[\frac{\sqrt{(u_j-u_{j-1})^2 + (v_j - v_{j-1})^2}}{h} \geqslant \delta_j\right] \leqslant p_j^T, \quad (j = 1, \cdots, N) \tag{3}$$

$$p[(1-\gamma)a_{Peak} \geqslant a^T_{Peak}] \leqslant p^T_{Peak}; \quad p[(1-\gamma)\sigma_\alpha \geqslant \sigma^T_\alpha] \leqslant p^T_{RMS}, \quad \alpha = x,\ y,\ \theta \tag{4}$$

$$\boldsymbol{x} \in \boldsymbol{X} \subset D^L \tag{5}$$

The first term of the weighted-sum objective function is the aggregation of material cost (with the ith material density ρ_i, element length l_i, cross-sectional area x_i and unit cost C_U) and STMD cost C_D as

$$C_D = (16.1m^* + 1.9)\gamma^2 - (6.8m^* + 1.7)\gamma + (1.5m^* + 2.2) \tag{6}$$

where m^* and γ are the first-order generalized mass and designated acceleration reduction level (ARL) [41], respectively. For example, when m^* ranges from 1.6 to 2.4 ($\times 10^7$ kg), C_D ranges from 3.99 to 5.08 (Million USD) conditioned under $\gamma = 0.4$. The coefficients in Eq. (6) vary slightly for different structural system, but the expression does involve the most essential factors that influence the total cost of STMD. Therefore, it is accurate enough to guarantee an optimal balance between structural member cost and STMD cost. Note that γ can be either defined as design variable or fixed.

Then we use a hierarchical serviceability PBWE framework to envelop the multi-level performance requirements [42]. Generally, there are two types of risk modeling approaches in PBWE. One approach is the widely employed design wind speed approach, in which the probability of failure (PF) and the corresponding risk are the functions of design wind speed. Another "fully-probabilistic approach" [10] convolves the PFs conditioned under mean wind speed with the PDF of mean wind speed, and derives the overall PF over time with a failure recurrence interval [8]. To keep consistency with conventional wind-resistant design concepts, we model the risks in the former way, and the latter approach could be very promising for life-cycle cost modeling.

Then each performance requirement is characterized with a mean wind speed and recurrence interval. Violation of elastic drift criteria indicates damage on NSEs and corresponds to design wind speed with a return period of 50 years. Probabilistic constraints in (2) and (3) define the maximum PFs (6.68%) [43] of p_D and p_j for atop deflection and inter-story drift ratio with peak thresholds $\delta_{Top} = 1/500$ and $\delta_j = 1/400$ (H and h are the building and story height), respectively. The corresponding three constraints are imposed on the along-wind response U, crosswind response V and response in the most unfavorable direction, respectively. Habitability performances are defined according to the types of loss consequences [44]. When performance loss is incurred from the violation of vibration tolerance and occupant discomfort, frequency-related root mean square (RMS) threshold is preferable [45] and a 5-year-recurrence design wind speed is utilized. In severe cases, occupant perception of floor vibration would bring fear, alarm and anxiety at the very instance, and interruptions in business would result in significant loss, so a peak value threshold is imposed with a recurrence interval of 10 years [46]. Very frequent wind with 1-year-recurrence interval is related to the daily