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Performance-based multi-hazard topology optimization of wind and seismically excited structural systems

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ABSTRACT

The integration of topology optimization procedures into modern structural design frameworks is gaining interest as an innovative approach for achieving more efficient designs. To this end, probabilistic performance-based topology optimization frameworks have recently been proposed for the identification of optimal structural systems subject to extreme wind or seismic events considered in isolation. However, there are large geographic regions that are subject to both wind and seismic hazards. Therefore, the development of methods that can ensure that target performance metrics are met within a multi-hazard setting is a crucial step towards improving the reliability of structural systems.

This paper is focused on proposing a simulation-centered performance-based topology optimization framework for the identification of optimal structural systems for multi-hazard wind and seismic environments. A probabilistic performance assessment framework is firstly proposed based on synergistically describing the performance of wind or seismically excited systems. Based on this framework, a multi-hazard topology optimization strategy is proposed. In particular, the methodology is centered on the definition of an approximate optimization sub-problem that not only decouples the simulation-based performance assessment from the optimization loop, but also transforms the dynamic and uncertain optimization problem into an explicit static and deterministic problem therefore enabling its efficient resolution using any gradient-based optimizer. Optimal lateral load resisting systems that rigorously meet the probabilistic performance constraints set within the multi-hazard environment are therefore identified. A case study is presented demonstrating the potential of the proposed framework.

1. Introduction

Over the past decades, topology optimization has been adopted in various engineering fields as a robust computational tool for identifying optimal material layouts within prescribed design domains. In structural engineering, it has been explored as a mathematically driven approach for delivering more efficient and innovative load resisting systems as compared to designs obtained from more traditional empirical approaches [1–10].

While topology optimization has been traditionally framed in a deterministic setting [11,12], recent advances in computational capacity and speed is opening the door to the possibility of incorporating uncertainty in the problem setting [13–19]. This has allowed, among other things, the integration of state-of-the-art performance assessment methodologies–such as the Pacific Earthquake Engineering Research (PEER) Center's Performance-Based Design (PBD) framework [20–23]–to be integrated into topology optimization frameworks for the identification of optimal lateral load resisting systems [9,10]. The ultimate goal of combining modern PBD frameworks with topology optimization is to define conceptual design frameworks that synergistically allow the uncertain and dynamic nature of building systems subject to environmental excitation to drive the search for optimal load resisting systems. To achieve this goal, topology optimization has to be performed not only under uncertainty, but also within a dynamic setting. However, while extensive works have been carried out on uncertain static topology optimization problems [16–19,24–29], the same cannot be said for uncertain dynamic systems due to an increase in problem complexity. In this regard, Kareem et al. [7] introduced a framework that integrated computational fluid dynamics with topology optimization for the sequential shape and topology optimization of wind excited dynamic and uncertain tall buildings, Chun et al. [30–32] and Zhu et al. [33] proposed theoretical frameworks that integrate topology optimization with random vibration theories for structures subject to stationary stochastic excitation, and Bobby et al. [9,10] proposed a performance-based topology optimization framework for wind-sensitive tall buildings that explicitly model the dynamic and

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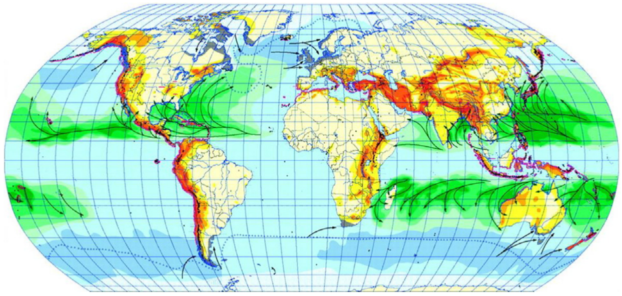

Fig. 1. World map of natural hazards. Earthquake hazard is shown in yellow-brownish colors while the wind storm hazard is shown in green colors [42]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

uncertain nature of the system.

The aforementioned efforts have focused, however, on a single wind or seismic hazard. While this may be deemed sufficient in the case of one dominant hazard, a number of studies have shown the need to consider the combined effects of different hazards if risk consistency is to be achieved in the design of buildings [34–38]. Under such conditions, the design of the structural system should be carried out in an integrated multi-hazard setting in order to achieve a structural performance that is consistent with owners' expectations and general societal objectives [37]. This situation has been documented by the designers of tall buildings in areas such as the West Coast of the United States, China, and Japan, where–as shown in Fig. 1–non-negligible wind and seismic hazards are present [39,40]. A common situation that is often encountered when building in these areas is that a system designed for wind will yield poor performance when subject to seismic actions or vice versa [39]. One of the reasons for this performance inconsistency can be traced back to how the structural response under wind actions is mainly governed by the first mode while, in the case of seismic actions, higher modes can contribute significantly to the structural response [41]. These situations can only be effectively treated through the development of multi-hazard design approaches.

Within this context, the primary goal of this work is to develop a simulation-centered performance-based topology optimization framework for the identification of optimal structural systems for multi-hazard wind and seismic environments.

2. Problem definition

2.1. Problem setting

The main goal of this work is to define a framework for topology optimization of dynamic and uncertain structural systems within a multi-hazard setting. More specifically, the aim is to obtain topologies that minimize the amount of material within a prescribed design domain while ensuring that the structural system satisfies a number of predetermined performance constraints. From a formal standpoint, this problem statement can be expressed as:

$$\begin{aligned} \min_{\boldsymbol{\rho}} \ & V(\boldsymbol{\rho}) = \sum_{e=1}^{n} \int_{\Omega_e} \rho_e \mathrm{d}\Omega_e \\ \text{s.t.} \ & \lambda(dm_j;\boldsymbol{\rho}) \leqslant \lambda_{0j}, \ j = 1,\dots,N_c \\ & 0 \leqslant \rho_e \leqslant 1 \end{aligned} \tag{1}$$

where $\boldsymbol{\rho} = \{\rho_1,\dots,\rho_n\}^T$ is an element-wise normalized material density vector that is generally related to an independent design variable vector $\mathbf{x}$ through a filter operator Ξ_e such that $\rho_e = \Xi_e(\mathbf{x})$, n is the total number of elements composing the discretized design domain, Ω_e denotes the domain of element e, V is the total material volume of elements within the design domain, $\lambda(dm_j)$ is the mean rate of exceeding the jth damage threshold dm_j, λ_{0j} is the target mean failure rate for the jth performance constraint, and N_c is the total number of performance constraints.

The main challenge in solving the above problem lies in the treatment of the mean failure rates $\lambda(dm_j)$ which, in this study, are framed in terms of the PEER Center's Performance-Based Design (PBD) framework [20–23]. This implies that they are described by probabilistic integrals that are implicit in terms of the design variables $\boldsymbol{\rho}$. This causes two levels of difficulty: firstly, their evaluation (whether through simulation or analytical approaches) is computationally challenging as it involves repeated evaluation of the dynamic system; and secondly, as they are implicit in terms of the design variables $\boldsymbol{\rho}$, which significantly hinders the evaluation of their gradients, i.e. sensitivities, with respect to $\boldsymbol{\rho}$. The need for the gradients of $\lambda(dm_j)$ with respect to $\boldsymbol{\rho}$ lies in the desire to use gradient based optimization algorithms for solving the problem outlined in Eq. (1). Indeed, topology optimization problems are inevitably high-dimensional (thousands of design variables) due to the necessity to adequately discretize the material design domain, therefore making the use of gradient based optimization algorithms extremely desirable if solutions are to be found in a reasonable amount of time.

A first step towards finding an efficient strategy for overcoming these difficulties is to observe that the failure rate functions $\lambda(dm_j)$ are strictly monotonic in most cases of practical interest. Therefore, the original constraints can be written in an equivalent inverse form [43] whose sensitivities–after appropriate mathematical manipulations that will be presented in the following–can then be estimated using the efficient adjoint methods. In particular, the inverse constraints take the form:

$$dm_j^{(\lambda_{0j})}(\boldsymbol{\rho}) - dm_j \leqslant 0 \tag{2}$$

where $dm_j^{(\lambda_{0j})}$ is the damage threshold corresponding to the target failure rate λ_{0j} defined as:

$$dm_j^{(\lambda_{0j})}(\boldsymbol{\rho}) = \lambda_{dm_j}^{-1}(\lambda_{0j};\boldsymbol{\rho}) \tag{3}$$

where $\lambda_{dm_j}^{-1}$ is the inverse of the mean failure rate function. As a result, the original formulation of Eq. (1) can be rewritten in terms of inverse constraints as:

$$\begin{aligned} \min_{\boldsymbol{\rho}} \ & V(\boldsymbol{\rho}) = \sum_{e=1}^{n} \int_{\Omega_e} \rho_e \mathrm{d}\Omega_e \\ \text{s.t.} \ & dm_j^{(\lambda_{0j})}(\boldsymbol{\rho}) \leqslant dm_j, \ j = 1,\dots,N_c \\ & 0 \leqslant \rho_e \leqslant 1 \end{aligned} \tag{4}$$

In order to solve the problem stated in Eq. (4) for uncertain and dynamic systems subject to multi-hazard wind and seismic environments, a framework for firstly assessing the multi-hazard thresholds $dm_j^{(\lambda_{0j})}$ and secondly estimating their sensitivities with respect to $\boldsymbol{\rho}$ is required. The following sections will outline a simulation-based strategy to this end.

2.2. Design domain

The focus of this work is on finding optimal lateral load resisting systems, specifically the exterior bracing scheme. Therefore, the design domain (i.e. where the bracing system is allowed to exist) is taken as the exterior skin of the building, as illustrated in Fig. 2. This space is then discretized with an appropriate Finite Element (FE) mesh. In general, building systems will have a secondary system composed of beams, columns and floor systems that are responsible for transferring vertical loads to the foundations. While the topology of this secondary system is not to be designed here, it provides a source of non-negligible stiffness that can influence the optimal lateral load resisting systems and therefore must be modeled together with the design domain. In light of this, the FE model of the "complete system" is defined as the