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Investigating the structural response of high-rise buildings under earthquake and wind hazards scenarios

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SUMMARY
The structural integrity of high-rise buildings is constantly threatened by wind-induced excitations due to their slenderness and height. Although the slender geometry of such buildings requires a design, focused on managing persistent dynamic vibrations, current international regulatory frameworks usually treat wind and seismic load effects as separate factors. This decoupling, based on the statistical rarity of simultaneous extreme events, may inadvertently overlook the cumulative displacement-induced damage sustained by non-structural systems. This study examines the structural response of a set of tall buildings, parameterized by height and designed for various areas within the Mediterranean region, when simultaneously or sequentially subjected to seismic and wind loads.

Keywords: high-rise buildings, structural response, inter-story drift, multi-hazard analysis

1. INTRODUCTION

The increasing frequency of natural disasters (specifically seismic activity and extreme winds) necessitates a paradigm shift in structural engineering. Traditional single-hazard design is increasingly viewed as insufficient and replaced by comprehensive multi-hazard risk assessments [Kwag and Gupta 2017; Kwag et al. 2021]. This transition is driven by the significant economic implications of structural performance; indeed, the cumulative lifecycle repair costs for modern buildings often rival or surpass the original capital expenditures [e.g., Cui and Caracoglia 2018; Caracoglia 2018]. For slender high-rise structures, the challenge is particularly acute. Modern design must account for concurrent lateral excitations [Ciabattoni et al. 2024], as height-dependent wind speeds and seismic accelerations impose disproportionate demands on non-structural components [Rizzo et al. 2020; Rizzo et al. 2021].

While the primary load-bearing systems may remain within their elastic limits during such events [Rizzo et al. 2024], the superimposed pressure loads frequently compromise secondary elements, such as those located on the façades. Although the perfect synchronization of peak-intensity events remains statistically very rare, the temporal overlap of sustained wind loads, and a moderate seismic event represents a critical risk factor [Rizzo et al. 2024]. This study addresses this vulnerability by establishing a stochastic simulation framework that quantifies these concurrences, focusing on the tectonically active regions of Italy, Greece, and Turkey. The research utilizes numerical expansion techniques to augment the underlying empirical dataset. The collected data sets, providing the seismic and wind loads, are applied to a set of tall buildings parameterized by height (considering a total of eight heights ranging from 50m to 300m), designed according to local regulations and site-specific baseline loads. The response of these case studies is investigated in terms of inter-story drift to evaluate the maximum deformation of the façades and compare it against regulatory limits.

2. METHODOLOGY

This study analyses the effects of simultaneous significant seismic events and non-negligible wind velocities on a total of 736 tall buildings of varying heights within the Mediterranean region. Italy, Greece, and Turkey were selected as representative case studies due to their high seismicity and the frequent landfall of windstorms, recorded over the last 50 years. The analysis encompasses 92 cities (24 in Italy, 24 in Greece, and 44 in Turkey). Seismic parameters (site latitude and longitude, date and time of the event, and Peak Ground Acceleration) were aggregated from the European Strong-Motion (ESM) and ITACA databases. Simultaneously, reference mean wind velocities (U) at a 10 m height were extracted from the ERA5 hourly dataset, spatially and temporally synchronized with each seismic record. This dataset merging yielded two distinct datasets: the first regarding daily average wind speeds, and the second regarding instantaneous mean wind speeds at the exact hour of the seismic event. Significance thresholds were defined as PGA = 0.025g (24.5 cm/s²), based on MPS04-S1, while the threshold for wind is $U = 5$ m/s [Rizzo et al. 2024].

The empirical dataset was subsequently expanded using Monte Carlo simulation to mitigate disparities in record lengths and bridge some gaps in historical data [Yu et al. 2025]. Through 10,000 iterations, uniformly distributed input random variables were mapped to physical variables using the Inverse Cumulative Distribution Functions (ICDF) of the fitted marginals. To standardize the results, a 52-year observation period (based on the Ancona record, the dataset with the longest duration) was adopted as a reference, utilizing a correction factor to normalize site-specific durations.

The final phase involves a static reliability analysis using the CAARC benchmark building [Melbourne 1980; Li et al. 2020], used as a reference and preliminary of the simulation framework. Eight building model variants were modelled (Figure 1) to assess height-dependent sensitivity (heights equal to 50m, 75m, 100m, 125m, 150m, 200m, 250m, and 300m), maintaining volumetric consistency through a geometric scale factor. The base prototype for each height variant was first modelled using the Finite Element Method (FEM) in SAP2000. All eight models were designed considering the baseline actions of a case study, performing a response spectrum dynamic analysis for seismic loads and evaluating the wind profile with equivalent static wind loads. The FEM prototype was then calibrated into a lumped mass system, after adapting mass and stiffness elements according to the specific seismic and wind load baseline for each of the 92 sites of interest.

The seismic and wind event pairs, extracted from the expanded datasets, were converted into equivalent static forces applied to the lumped mass model, subjected to height-dependent kinetic pressures and seismic base accelerations. The analysis focused on the X-direction (along-wind direction), quantifying: inter-story drifts and absolute floor displacements; and the performance of glass-aluminium “stick” curtain wall systems as the primary reliability analysis metric. The total lateral floor displacement (f_{sw}) was calculated through the superposition of independent seismic (f_s) and wind-induced (f_w) responses. Structural compliance was verified against the serviceability limit states, prescribed by UNI EN 13116 (2024).

Analyses were performed in MATLAB R2024b, and the finite element models (FEM) of the buildings were developed in SAP2000.

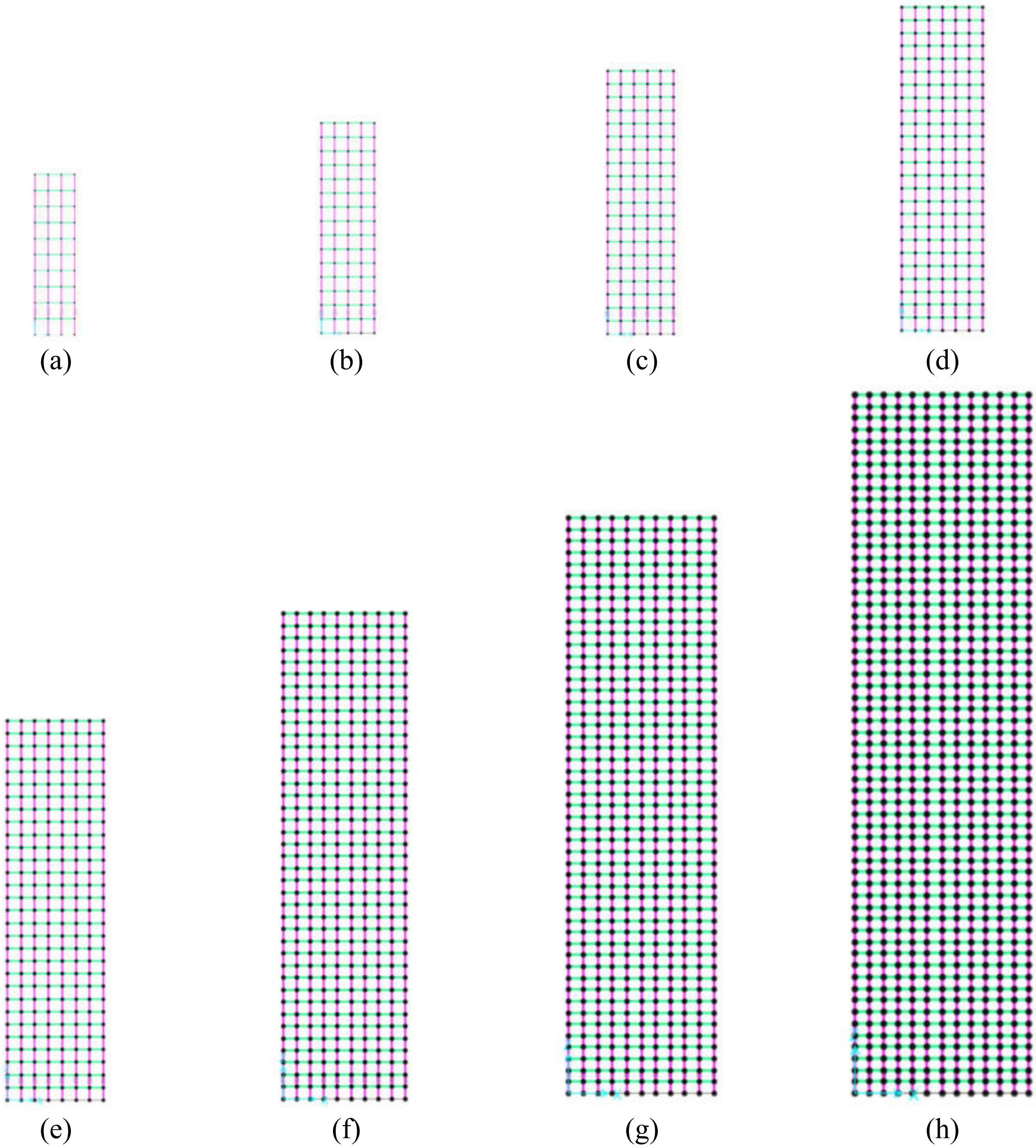

Figure 1. FEM models, front (elevation) view on the XY plane for a prototype building with variable height, 50m (a), 75m (b), 100m (c), 125m (d), 150m (e), 200m (f), 250m (g), 300m (h)

3. RESULTS AND DISCUSSION

From a structural performance perspective, applying synchronized loads to prototype buildings with variable heights demonstrates that neglecting hazard concurrence leads to an underestimation of lateral displacement demands. As the structural height and slenderness increase, the combined effect of seismic inertial loads and wind pressure loads results in inter-story drifts that often exceed serviceability limit states. Notably, Monte Carlo simulations indicate that, under simultaneous loading, the relative horizontal displacement of curtain wall systems often exceeds the 21 mm [UNI EN 13116] operational threshold, defined by regulatory standards. Simulation results suggest that, while primary load-bearing members may remain safe, non-structural components are at high risk of localized failure (e.g., glass breakage or large frame deformation) when wind load effects are not negligible during seismic events.

4. CONCLUSIONS

This study demonstrates that the occurrence of moderate seismic activity alongside significant wind loads poses a significant risk. The stochastic structural analysis framework, validated through Monte Carlo simulations, reveals a significant regulatory shortcoming: current structural codes, which treat these hazards as independent, could lead to a substantial underestimation of the actual demand for non-structural elements placed on the façade of high-rise buildings.

Structural applications to benchmark buildings reveal that concurrent loading disproportionately affects non-structural components, frequently pushing façade's curtain wall elements beyond their operational limit of 21 mm. These findings suggest that, for slender medium-to-high-rise buildings, a multi-hazard design approach is essential to prevent localized failures and mitigate the substantial socio-economic costs associated with non-structural damage.

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