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Developing wind-induced failure probability models for lightweight industrial roofs

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SUMMARY
Wind-induced failures on industrial roofs represent one of the causes of huge economic losses for industrial facilities. Several failure mechanisms for industrial roofs have been investigated for lightweight industrial roofs yet, there is limited studies providing robust catalogue for such industrial structures. In this study a probabilistic framework was implemented to develop a catalogue of fragility parameters representing a wide range of geometric variation of an idealized industrial structure. Using Monte Carlo simulations, the framework considered the parametric variation of roof pitch, building height, roof span, aspect ratio as well as the wind direction. The damage mechanism considered in framework is the punching failure at the fastener locations following for progressive damage and load redistribution. Four damage states were considered in the analysis, and several fragility curves were developed considering the various geometric combinations, damage states and wind directions. The results show that the influence of width and aspect ratio on the fragility parameter is generally direction dependent while roof pitch influence of fragility parameter holds consistently regardless of direction. The developed fragility functions are useful for wind induced risk assessment.

Keywords: wind vulnerability, interference, urban morphology

1. INTRODUCTION

Warehouses, manufacturing plants and similar industrial facilities are commonly built with lightweight steel roofing systems, which are structurally efficient, light and inexpensive. The same low self-weight leaves these systems exposed to wind damage, in particular under the uplift pressures produced by severe wind events (Lee & Rosowsky, 2005; Qin et al., 2023; Rosowsky & Cheng, 1999; Sivapathasundaram & Mahendran, 2016; Stewart et al., 2016).
Unlike highly redundant structural systems, lightweight roofing assemblies offer few alternative load paths. The failure of a single fastening connection therefore transfers load to the adjacent fasteners, and this can trigger progressive or cascading failure of the roofing system (Konthesingha et al., 2015; Starossek, 2009).
Probabilistic methods have accordingly become more prominent in wind engineering and fragility assessment, especially for the vulnerability of industrial and low-rise building roofs. Stewart et al. (2016) combined resistance models with empirical and statistical descriptions of wind loading to derive fragility relationships for industrial roof assemblies. Uncertainties in aerodynamic coefficients, material strength and fastening properties were included explicitly. These uncertainties were then propagated by Monte Carlo simulation to produce fragility curves for reliability-based vulnerability assessment. Stewart et al. (2018) later extended the same framework to the effects of a changing wind climate on the performance of roof sheeting.
The present study addresses the probabilistic fragility assessment and cataloguing of lightweight steel industrial roofing systems under wind uplift. The objective is a suite of fragility functions spanning a broad range of roof geometries and structural characteristics, with the uncertainties in both wind loading and structural resistance included explicitly.

2. METHODS

The representative structure is an idealised industrial facility with a lightweight steel roof, plan dimensions of width B = 10 m and length L = 20 m, height h = 6 m and roof pitch α = 5°. Figure 1 shows the zones and the associated C_{pe} coefficients for the structure examined following provisisions form (Consiglio Nazionale delle Ricerche, 2018). The pressure coefficients depend on the roof geometry, so they are recomputed automatically for every roof geometry examined during the simulation.

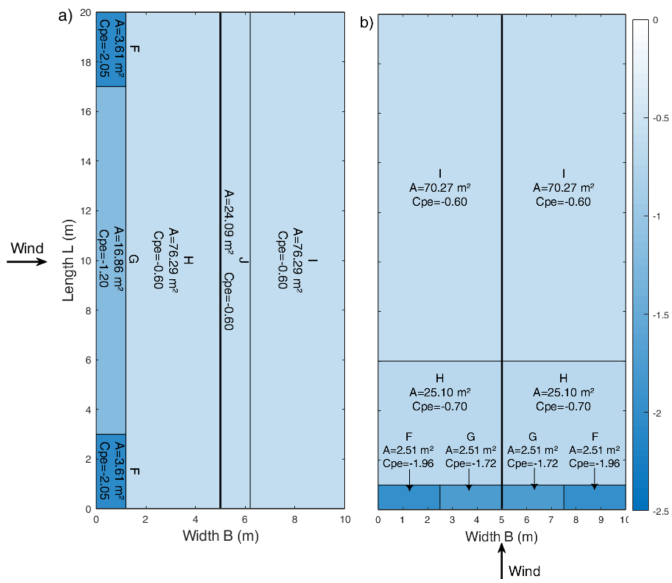

Figure 1. Estimated C_{pe}: (a) wind direction perpendicular and (b) parallel to the roof ridge.

Fragility was estimated through Monte Carlo simulation, with the stochastic variability of the resistance parameters sampled explicitly. The key simulation parameters are treated as random variables, which accounts for the uncertainties in wind loading, material properties, geometric tolerances and resistance modelling. Mean values and coefficients of variation (CoV) were taken from the literature, from experimental studies and from international standards. Each simulation assigned a punching resistance to every bolt on the roof, with random variation of bolt diameter, steel thickness, material strength, tributary area and aerodynamic coefficients. The demand on each connection followed from the peak wind velocity v_p, which produced the wind pressure on the roof. The simulation advanced in discrete steps of increasing wind velocity, and the load of any bolt found to have failed was redistributed to the neighbouring bolts. Redistribution followed the model of Konthesingha et al. (2015). The redistribution procedure continued until no further failures occurred at the given wind intensity. The wind velocity was then raised and the procedure repeated. Fragility curves were constructed from these simulations for four damage states (DS), selected to represent different levels of system degradation. Once the probability of failure has been evaluated for each ith limit state and for increasing wind-speed values, a lognormal distribution is fitted to the data, and the resulting fragility parameters are reported in terms of median θ_i standard deviation of the natural logarithm of wind speed, β_i. These parameters are then used to develop the fragility curves following the equation:

$$P[DS \geq DS_i | V_p = v_p] = \Phi\left(\frac{\ln(v_p) - \ln(\theta_i)}{\beta_i}\right) \tag{1}$$

3. RESULTS

Figure 2 shows the response of the industrial roof under extreme wind events. Failure in the system is initiated at low values of v_p for damage state DS1. The remaining damage states require considerably higher velocities before the probability of exceedance becomes meaningful. This behaviour is also expected because wind pressures decrease toward the inner portions of the roof, making the uplift and loss of large roof areas less likely. Furthermore, the detachment of individual panels makes the progressive pull-off of adjacent panels more difficult, thereby limiting the propagation of damage. For instance, damage state DS4, which corresponds to damage affecting more than 50% of the total roof area, reaches a probability of exceedance of about 10% when peak wind velocities exceed 80 m/s.

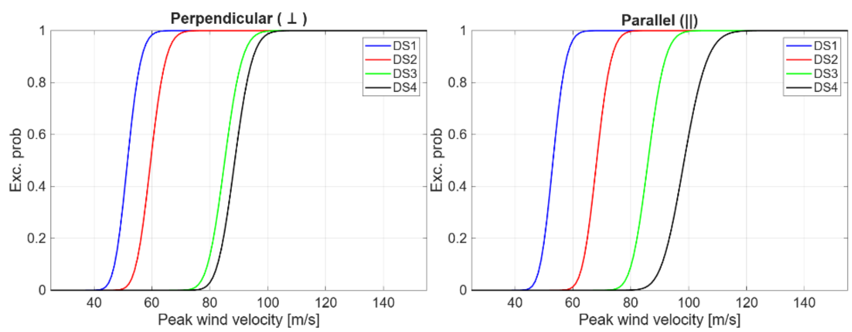

Figure 2. Fragility curves for punching failure across the four damage states and directions.

Fragility analyses covered roof pitch angles α ∈ {0°, 5°, 10°}, building heights h ∈ {6, 9, 12} m, roof widths B ∈ {10, 20, 30, 40} m and plan aspect ratios L/B ∈ {1, 2, 3, 4}, for a total of 144 unique configurations. Fragility curves were generated for each configuration across the four damage states (DS1 to DS4) and for two wind directions, perpendicular and parallel. The parameters θ_i and β_i were extracted in all cases.

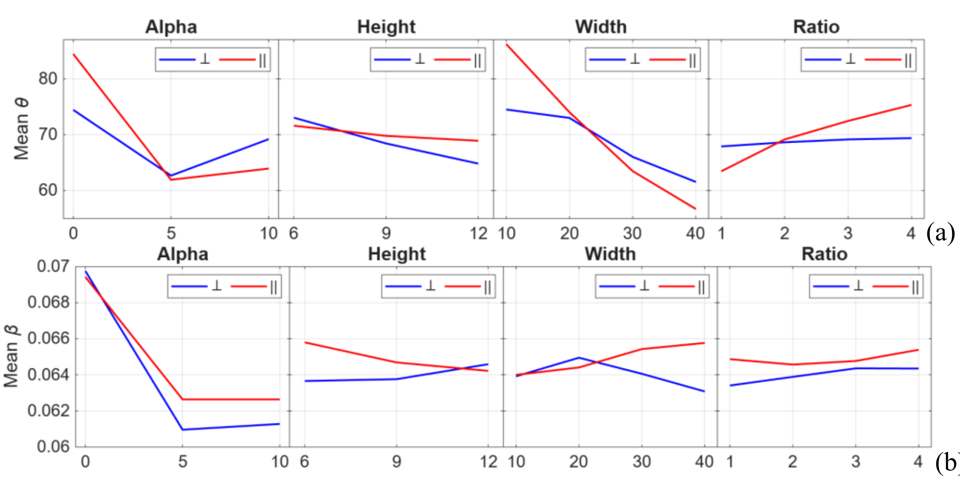

Figure 3. Main Effect Plot for (a) median parameter (b) dispersion parameter

Figure 3 presents the main effect plot. It shows how variations in the geometric characteristics influence the fragility parameters when wind direction is treated explicitly in the perpendicular and parallel directions. Isolating the individual contribution of each variable makes the variation in the median fragility parameters ($\theta_{\perp}$ and $\theta_{\parallel}$) clearly visible.

4. DISCUSSION AND CONCLUSION

The influence of roof geometry is not consistent and depends on both damage state and direction. Roof pitch, building height and roof width all modify the initiation of exceedance probability, but not uniformly across directions.

Width is the dominant driver of fragility in both directions, although its magnitude changes with wind direction. Height significantly affects the median fragility only in the perpendicular direction. Roof slope strongly influences both the logarithmic standard deviation and the median of the fragility curves, and this holds regardless of wind direction.

The aspect ratio L/B has a direction-dependent effect. It has no significant influence on median fragility in the perpendicular direction, but a significant positive effect in the parallel direction.

These results confirm that lightweight steel industrial roofing systems show a complex fragility response under extreme wind loading, dependent on both configuration and direction. The proposed probabilistic framework provides a basis for performance-based wind engineering applications, vulnerability assessment and risk-informed evaluation of industrial roofing systems.

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