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Benchmarking LES simulations using experimental databases for fragility curve development

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SUMMARY

Wind is one of major natural hazards, often involved in multi-hazard scenarios that combine extreme winds, heavy rainfall, lightning, and so on. Low-rise buildings are largely diffused in many parts of the world and particularly susceptible to wind hazards, representing one of the most vulnerable structural typologies. The long-term goal of this research is to develop fragility curves for typical low-rise buildings subjected to synoptic and non-synoptic winds. In this paper, two benchmark buildings are investigated by wind-tunnel (WT) tests and Computational Fluid Dynamics (CFD) simulations, in order to obtain pressures time domain records representative of neutral atmospheric boundary layer wind actions. The two buildings are selected as archetypes of civil masonry buildings and industrial buildings in the Italian territory.

Keywords: wind hazard, benchmark, WT testing, CFD simulations, fragility curve.

1. INTRODUCTION

Wind is one of major natural hazards often leading to multi-hazard scenarios that cause substantial damage to the built environment. Synoptic winds, such as atmospheric boundary layer (ABL) winds, and non-synoptic winds, such as thunderstorm downbursts and tornadoes, not only involve primary hazards like extreme winds, heavy rainfall, lightning, but may also trigger secondary hazards, such as flooding, landslides, and debris impacts thus creating a multi-hazard scenario (Sköld Gustafsson, 2023). Being able to reduce the magnitude of such events is unfortunately beyond the capabilities of wind/civil engineer experts. However, wind and civil engineers can work to reduce the vulnerability of structures and infrastructures. Performance Based Engineering (PBE) has gained interest in the last years in structural design. Developed by the seismic engineering community, this approach can be adapted to other hazards, such as wind, leading to the development of Performance Based Wind Engineering (PBWE) providing a robust framework with fragility curves serving as a fundamental component to quantify structural damages (Gavanski and Kopp, 2017). Such curves provide a quantitative relation between an incident *hazard intensity measure* and the resulting *probability of reaching or exceeding a damage state* by ensuring the later development of loss estimation models, disaster risk assessment and PBE. In general, low-rise structures are among the most vulnerable to wind-driven hazards (Spence and Arunachalam, 2022). The long-term goal of this research project is to develop fragility curves for typical low-rise buildings subjected to synoptic and non-synoptic winds. At *stage 1*, historical wind events are examined primarily across Italian territory to identify their occurrence and the structural archetypes most affected. At *stage 2*, wind-tunnel (WT) tests and CFD simulations are executed on two structural archetypes identified in the *stage 1*, under neutral ABL winds and thunderstorm downburst winds. WT and CFD analyses will take into account the variation of parameters such as terrain roughness length, roof slope, and other relevant configurations. At *stage 3*, well-established and publicly available databases from WT tests conducted by other scientists on similar or identical structural archetypes are used for comparison. At *stage 4*, the results obtained from both WT and CFD analyses will be used to develop fragility curves to quantitatively assess the structural vulnerability of the archetypes to wind hazard. In this paper, only *stage 2* and *3* will be discussed for two archetypes subjected to a neutral ABL wind: (i) a civil masonry building and (ii) an industrial building. Experimental data for the two benchmarks are also obtained from different public databases, as a further term of comparison.

2. EXPERIMENTAL DATA

2.1. Wind-tunnel testing at GS Wind Tunnel facility

WT tests are conducted on the 1:100 scaled civil masonry building only at the closed-circuit Giovanni Solari (GS) Wind Tunnel of the University of Genoa, Italy. The masonry building represents a well-established archetype across the Italian territory. A case study previously adopted as a benchmark for seismic analyses and located in Pizzoli, L'Aquila, is considered here (Fig. 1a). For convenience, the dimensions are provided in Section 3. The model is tested for two configurations, with and without a surrounding environment. At this stage, only the isolated case is investigated. According to the Italian Research Council, two terrain categories for open and suburban exposure (II and IV) characterized by an aerodynamic roughness length (z_0) of 0.05 m and 0.30 m, respectively, are considered. The roughness fetch consists of vortex generators positioned at the beginning of the test section, along with cubic roughness elements distributed throughout the test chamber. The mean wind speed (U), turbulence intensity ($I_{u,v,w}$) and integral length scale ($L_{u,v,w}$) profiles and the power spectrum density are acquired in the empty chamber at the center of the turntable. Measurements are conducted at 10 vertical levels to verify the correct development of the ABL flow. Given the symmetric configuration of the building with respect to the along-wind component, tests are conducted over a 10° interval from 0° to 180°, with the additional directions 45° and 135° (Fig. 1b). Pressures are acquired on the building facades with 360 taps (Fig. 1c) at 800 Hz. Then, pressure coefficients (C_p) are calculated using the reference velocity (for the dynamic pressure) measured in the empty chamber at the building height (13.35 m full scale). Each run and time history is of sufficient length to ensure statistically meaningful peak analysis.

2.2. Benchmark data from public database

Experimental data for the benchmark industrial building were obtained from the University of Western Ontario (UWO) (Ho et al., 2005) and from the Tokyo Polytechnic University database (TPU, 2025). Both databases provide publicly accessible time-series wind-load data for generic low-rise gable-roof building models, with full coverage of pressure taps over all building surfaces tested in WT, that is 665 pressure taps for the UWO model and 128 taps for the TPU model. The selected cases correspond to an isolated building with a roof pitch of 4.8°. The height-to-breadth ratio is 1:3 for the UWO model and 1:4 for the TPU model, for both open and suburban exposure conditions.

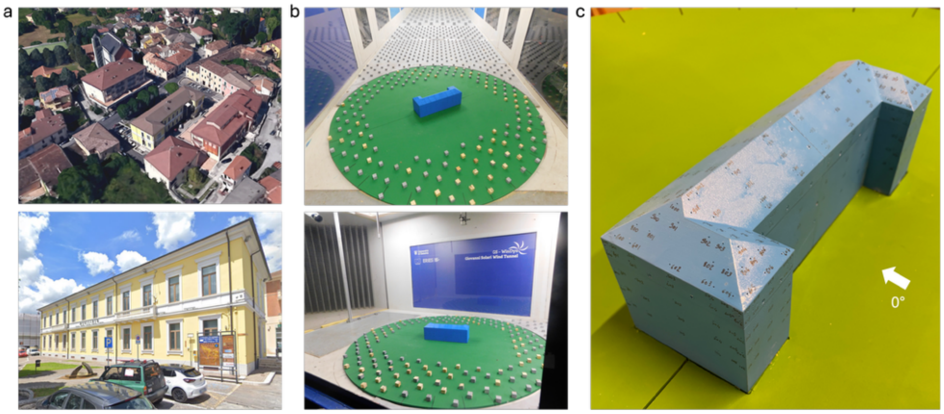

Figure 1: (a) Photographs of the masonry building located in Pizzoli, L'Aquila, Italy; (b) WT model at scale 1:100 for two wind directions; (c) close-up view of the pressure taps of the WT model for the wind direction 0°.

3. CFD SIMULATIONS

CFD simulations are carried out on the two benchmark cases using the large-eddy simulation (LES) approach. In order to avoid CFD models computationally demanding and therefore unsuitable for the development of fragility curves, two assumptions are made as a first attempt: (*i*) simulating only the wind direction of 0°; (*ii*) constructing so-called quasi-3D geometries with the actual building cross section (xz plane) and a spanwise dimension (y) defined arbitrarily by the user (i.e., 8 m) (Fig. 2). This approach is not new to the CWE community, having been widely adopted in the BARC benchmark study. A high-resolution computational grid is constructed for both benchmark cases, with a minimum grid size of 1.0×10^{-6} m on the building walls. The two grids counted about 3 million cells. The cell aspect ratio remains below 1.1 throughout the entire domain, while the Courant number varies during the simulation reaching a maximum value of 0.30. The min y^+ value is about 50 across the ground surface and below 1 on the building walls. The synthetic turbulent inflow method *SynInflow* developed by Patruno and Ricci (2018) is adopted here by using the U and L values obtained from WT tests (see Section 2), along with the corresponding vertical profiles of turbulence intensity. For the sub-grid scale turbulence model, the dynamic evaluation of Smagorinsky constant is used to model the small-scale turbulence. The simulation is initialized over two flow-through times (i.e., 100 s), after which 20 s are used for statistical analysis.

4. PRELIMINARY RESULTS AND CONCLUSIONS

This section shows some preliminary comparison in terms of $C_{p(mean)}$ obtained from the LES simulations and TPU database, for the industrial building. The WT results on the masonry building are currently in the post-processing, therefore, the comparison to LES results will be reported in the full paper. Figure 3 shows the $C_{p(mean)}$ distribution on the two archetypes, along with the vorticity (ω) field at a selected instant from the LES time history. This latter can support the reader in better understanding the $C_{p(mean)}$ distribution and provides a clear visualization of the vortex dynamics associated with the turbulent ABL flow. In general, despite the limitations of the quasi-3D model and the limited number of (pressure) taps available in the TPU database, the LES–TPU comparison shows very promising agreement in terms of $C_{p(mean)}$. Analyses of $C_{p(peak)}$ values, which are critical for damage assessment and cladding evaluation, are still ongoing and will be presented in the full paper, together with extensive comparisons against experimental results extracted from wind tunnel tests.

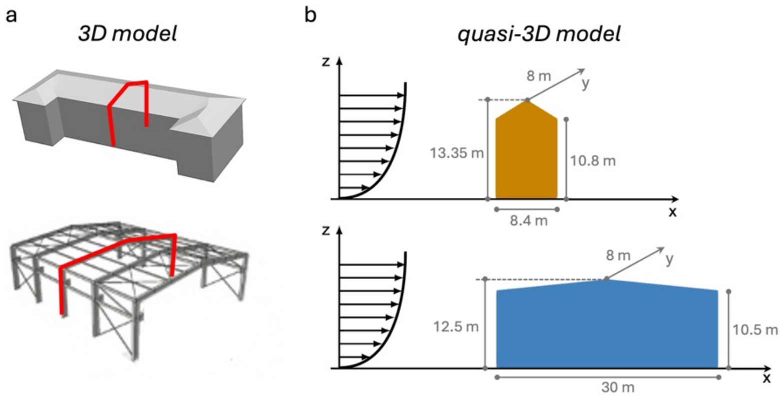

Figure 2: Benchmark cases: (a) 3D geometry models with an indication of the 2D sections (red line); (b) quasi-3D geometry models with dimensions used to construct the computational grid.

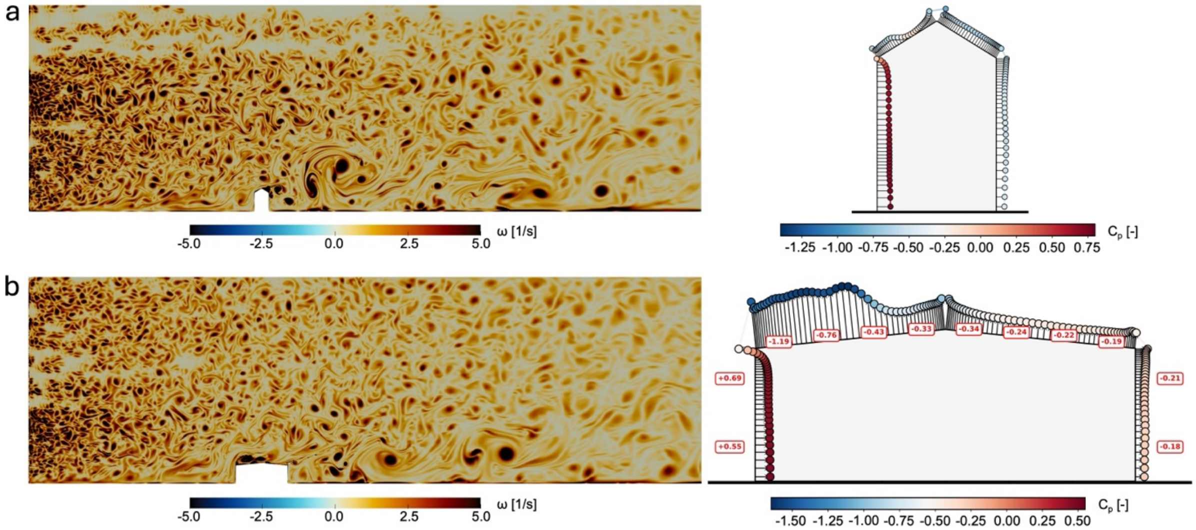

Figure 3: Vorticity (ω) contours by and mean C_p LES for the two archetypes (a,b), with comparison to the TPU database (red numbers) only for the industrial building (b).

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