WindMiL: Equivariant Graph Learning for Wind Loading Prediction

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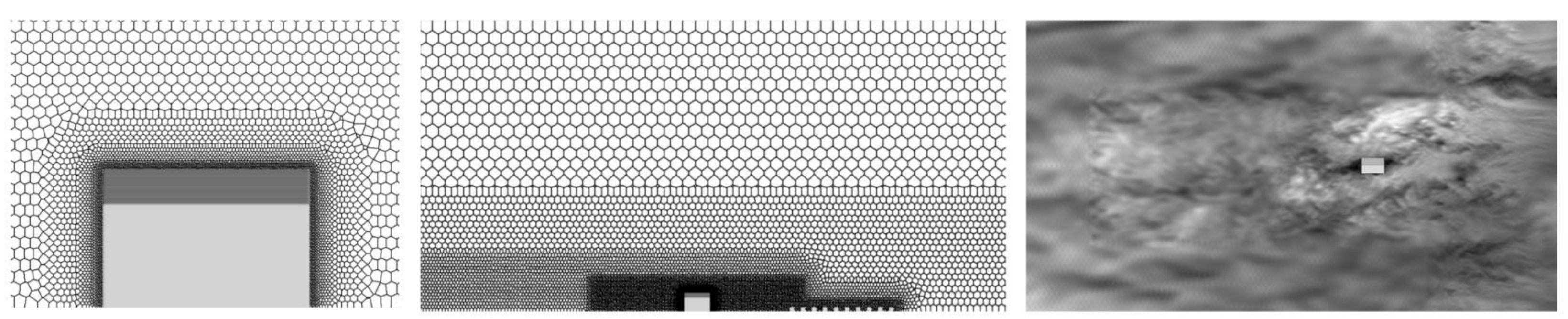
Motivation

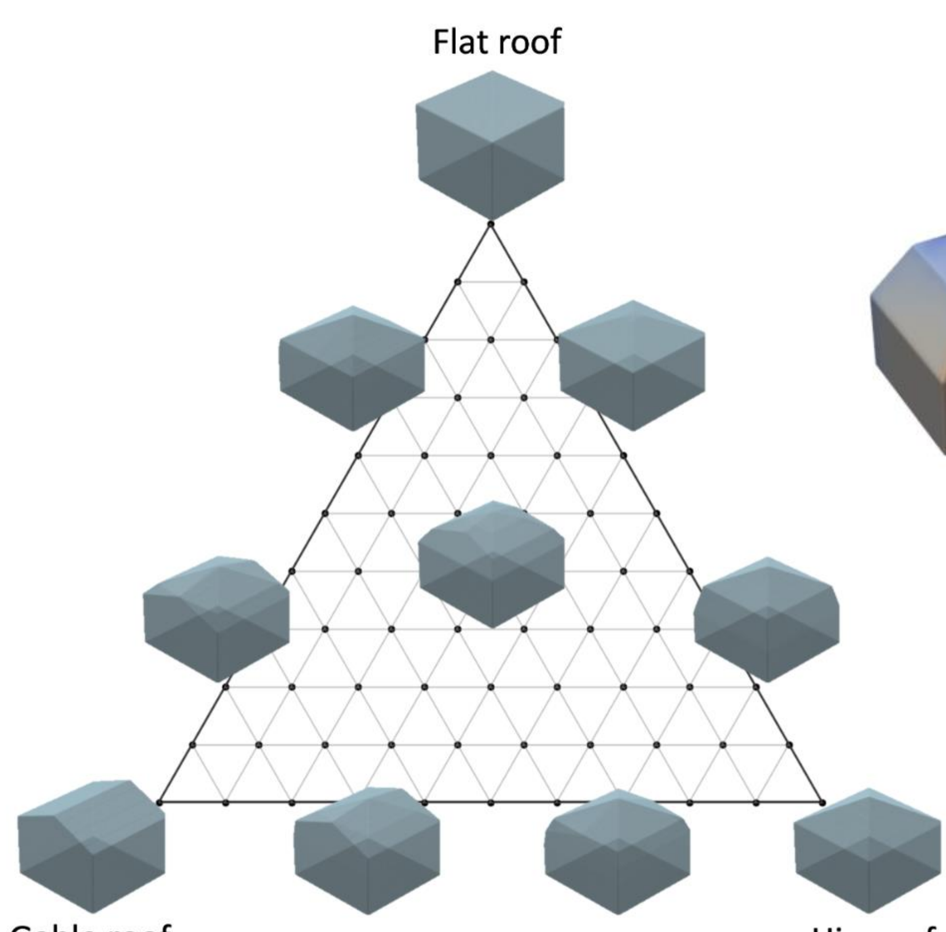
Accurately predicting wind loads on buildings is crucial for safety and sustainable design. Wind tunnels and Computational Fluid Dynamics are accurate but prohibitively expensive for engineering use; we propose **WindMiL,** a **reflection-equivariant GNN surrogate** for fast, accurate and physically consistent predictions.

Contributions

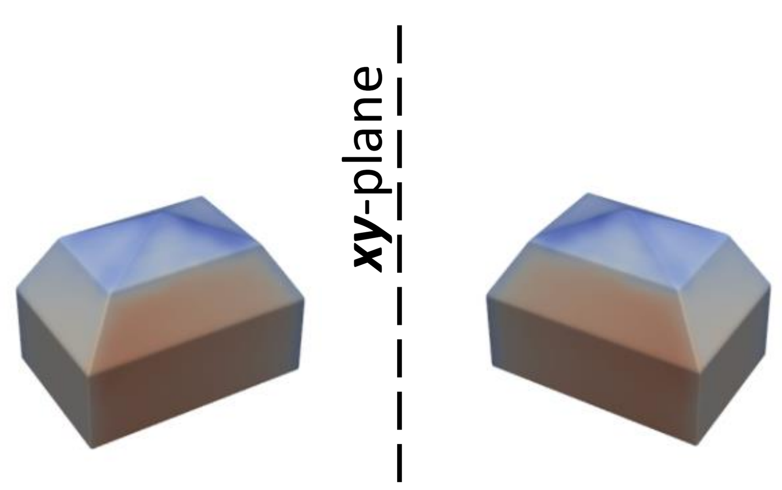
- **Dataset**: Large-scale dataset of wind loading on low-rise buildings by systematically varying roof morphologies and wind directions using LES.
- **Model**: Reflection-equivariant GNN that respects reflectional invariances to ***xy***-plane



Large-eddy Simulations (LES) of low-rise building



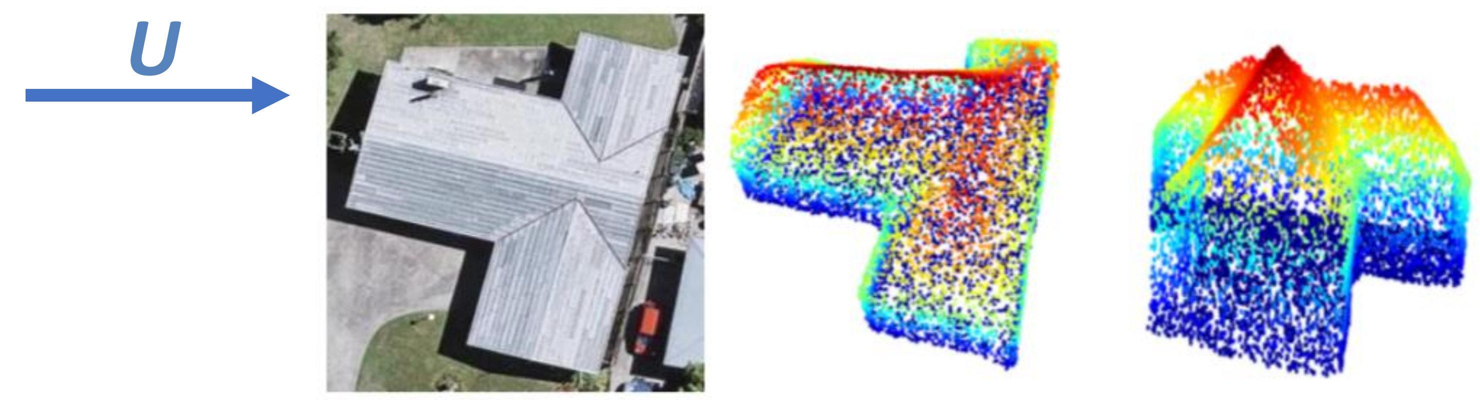
Convex hull of varying roofs



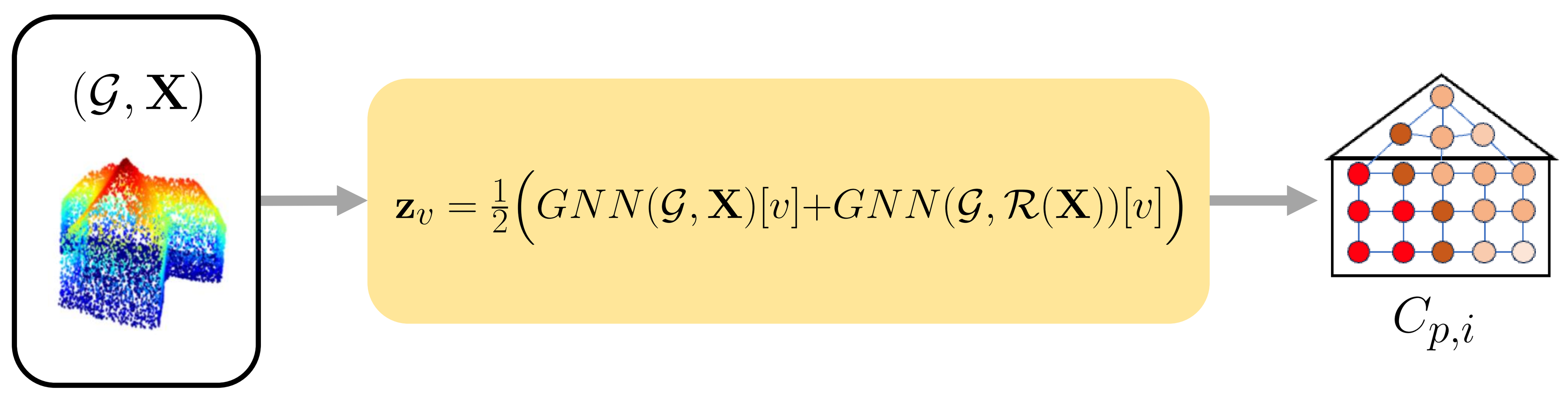
$$C_{p,i} = \frac{p_i - p_\infty}{\frac{1}{2}\rho U_\infty^2}$$

Graph representation & Model Architecture

Graph: Represent buildings as point-clouds where nodes are surface vertices with features $\mathbf{x}_v = (x, y, z, n_x, n_y, n_z)$; edges represent mesh connectivity.

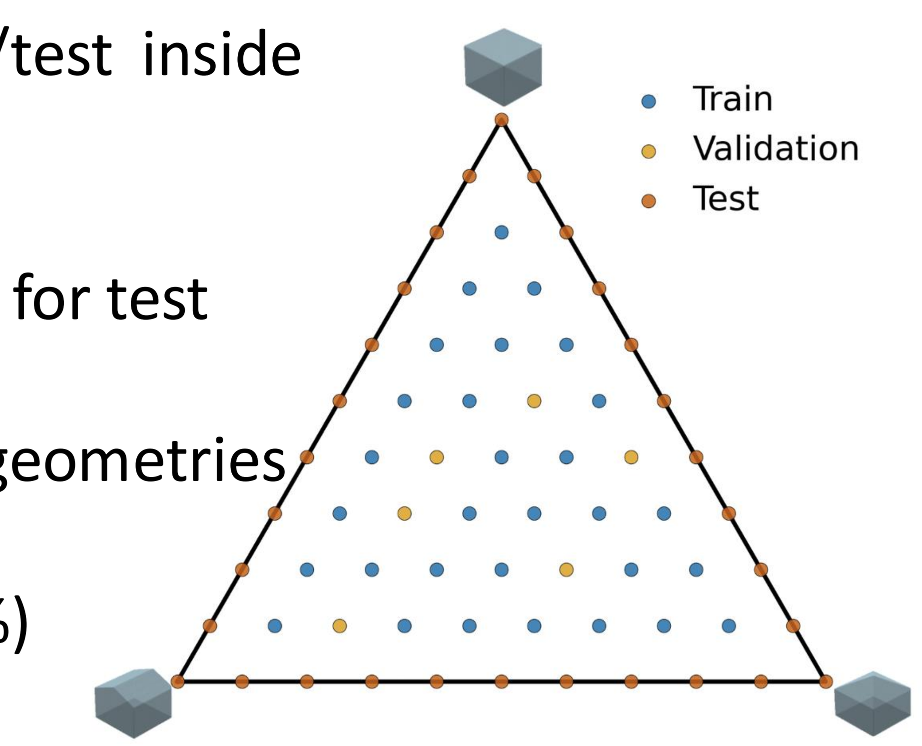


WindMiL equivariant model: Define $\mathcal{R} : (z, n_z) \mapsto (-z, -n_z)$ Graph structure and geometrical features of original and reflected building pass through the **same GNN** and resulting embeddings are averaged. Then, feed-forward predictor outputs the node-level $C_{p,i}$.



Evaluation Method

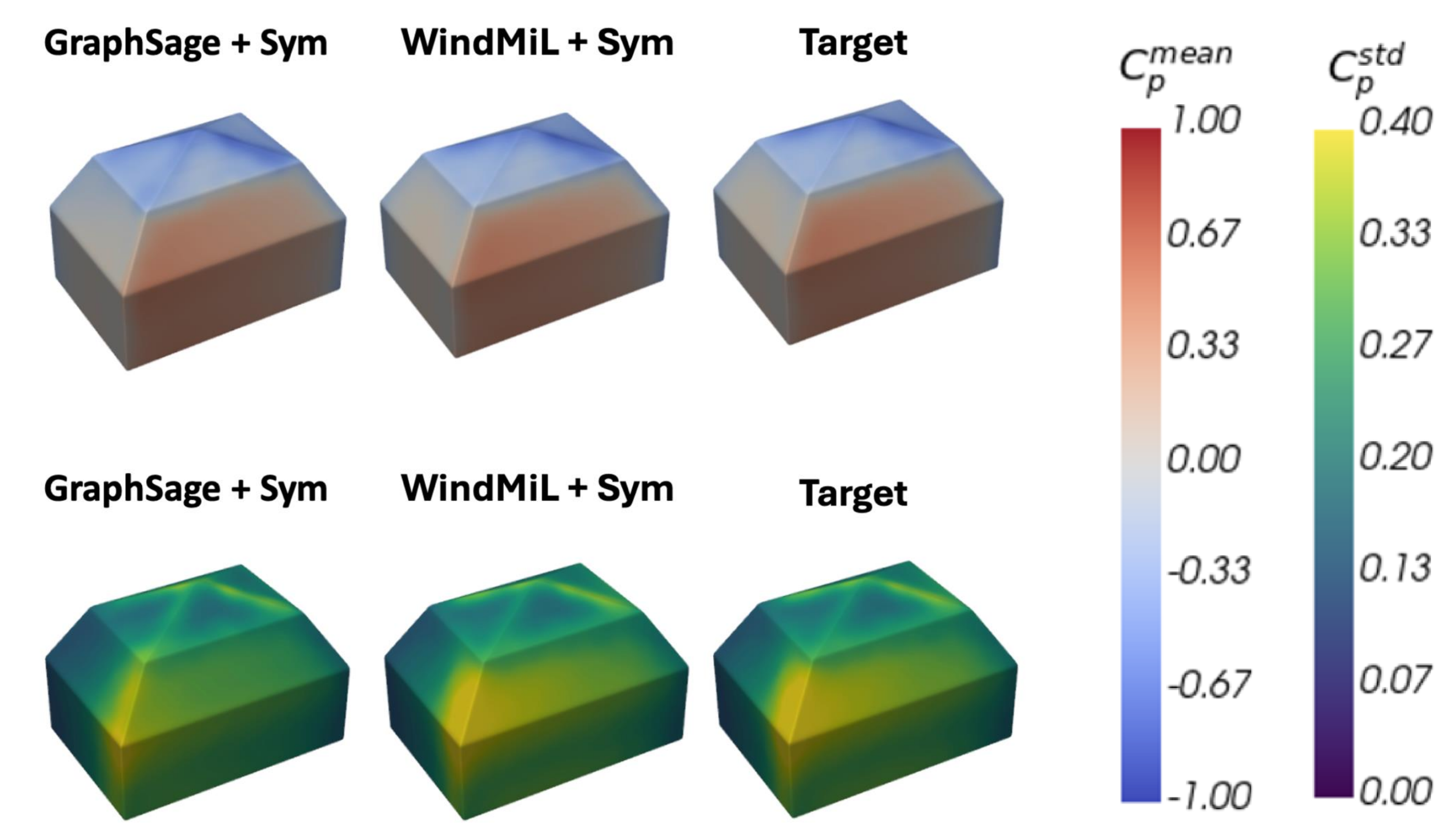
- **Interpolation:** random train/dev/test inside convex hull
- **Extrapolation**: hold out boundary for test
- **+Sym:** test set includes reflected geometries
- Metrics: MAE and hitrate (+/- 10%)



Results

- WindMiL outperforms non-equivariant GNN on extrapolation and +Sym tests, showing higher generalization.

Method	MAE	Hitrate (%)
GraphSage (Mean C_p)	0.033	94.98
GraphSage + Sym (Mean C_p)	0.054	84.67
WindMiL (Mean C_p)	0.035	94.16
WindMiL + Sym (Mean C_p)	0.034	94.69
GraphSage (Std C_p)	0.012	97.35
GraphSage + Sym (Std C_p)	0.020	91.57
WindMiL (Std C_p)	0.013	97.30
WindMiL + Sym (Std C_p)	0.012	97.33



Takeaways

- WindMiL **enforces reflection equivariance** and **outperforms** non-equivariant GNN.
- Significantly **reduces computational cost** to seconds, compared to LES, which requires 24+ hours.