# APPLIED CFD: SIMULATING THE BUILT ENVIRONMENT AND BEYOND

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# Let Me Introduce Myself



- **Assistant Professor**
  Faculty of Civil Engineering
  University of Belgrade

- Research Scientist
  University of Luxembourg

- European Evaluator
  H2020-MSCA-ITN & HORIZON-MSCA-DN

- Doctoral Studies
  Building Aerodynamics Laboratory
  Ruhr-University Bochum

- Magister & Dipl. Ing. Studies
  Faculty of Civil Engineering
  University of Belgrade

I'm a civil engineer with a background in wind-tunnel testing and CFD, applying these tools to real-world civil and environmental challenges — and recently expanding into data assimilation and machine learning to enhance simulation.

Karman vortex street, Heard Island, Wikipedia

# Let Me Introduce Myself



**Current Research projects**

- SeaDream – HORIZON-MSCA-SE-2023 (Partner)

Sustainable Marine Energy and Ecosystem Resilience Advancement through Digital Technologies and Real- Time Crisis Management

- ERIES – HORIZON-INFRA-2021 (PI of sub-project)

ERIES – FLOATINGSOLAR: Wind and wave effects on FLOATING SOLAR panels

**Previous Research projects**

- DATA4WIND – H2020-MSCA-IF-2019 (PI)
- DATA4WIND – FNR, 2020 (PI)
- SEEFORM – DAAD (Partner), etc.

**Industrial projects**

- Bridge on the river Sava, Serbia, consultant for Niemann&Partner
- High bay structure of Jysk-Nordic, Denmark, consultant for Niemann&Partner, etc.

# Applied CFD in Built Environment



## Civil Engineering Applications


*Source: www.flickr.com - "Roof Damage" by Beige Alert*

*Source: www.flickr.com - "JP Morgan Chase Damage" by AlphaTangoBravo / Adam Baker*


## Environmental Eng. Applications

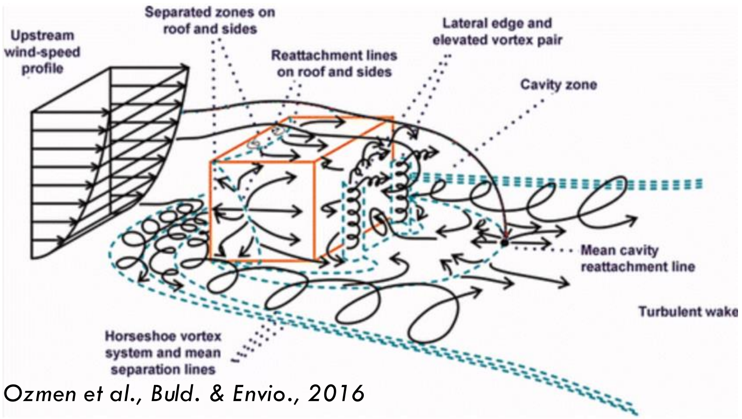

Boston Logan Airport, Source: www.propmodo.co... /can-tech-help-commercial-


China, Source: https://www.istockphoto.com/photo/china-shenzhen-skyscraper-gm969333552-264204925?searchscope=image%2Cfilm

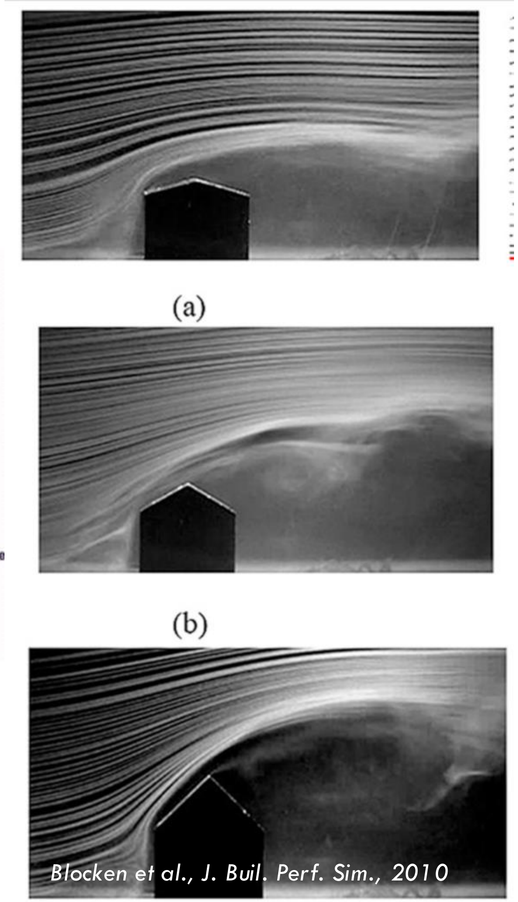
# Core Challenges



## Turbulent Flow & Geometric Complexity & Variability of Structures



*Ozmen et al., Buld. & Envio., 2016*



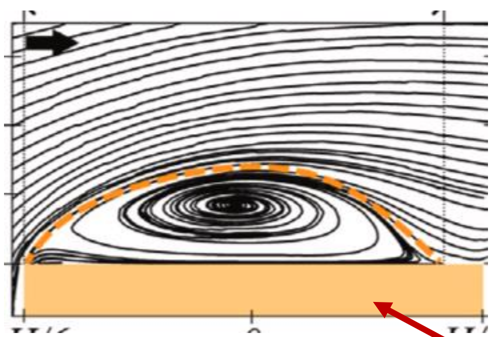
*Blocken et al., J. Buil. Perf. Sim., 2010*

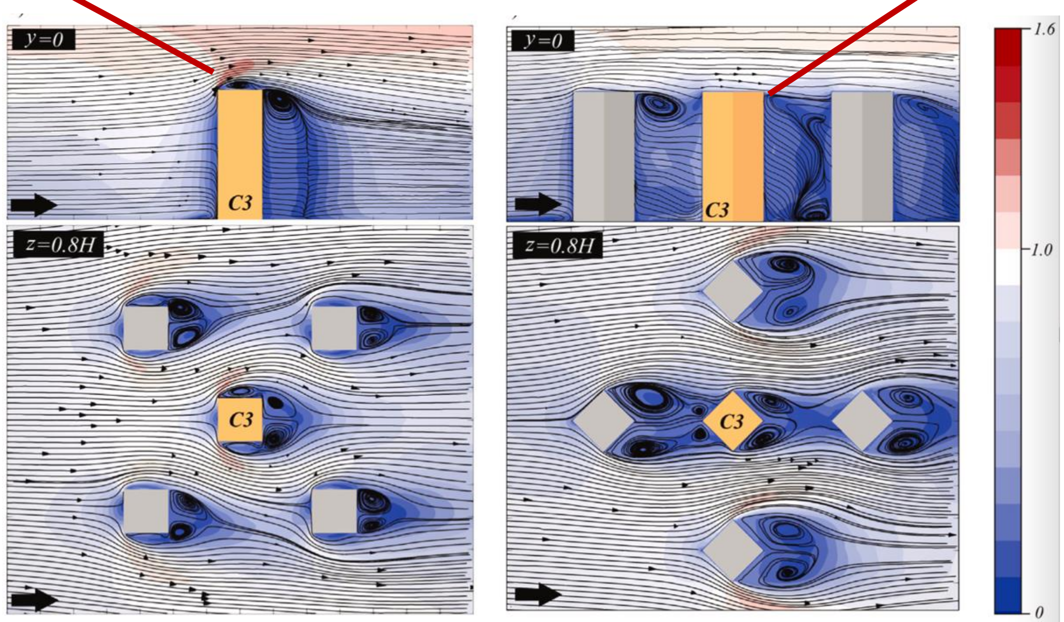

*Source: https://en.wikipedia.org/wiki/File:Civic_Center*

# Core Challenges



## Variability of Wind Direction





# Main Design Methods



## STANDARDS & CODES

### Pros

+ **Clarity and Consistency:**

Structured procedure that engineers can follow, reducing ambiguity in the design process.

+ **Safety and Reliability:**

Ensures that structures meet minimum safety and performance requirements.

+ **Standardization Across Projects**

+ **Legal and Professional Accountability**

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

**FINAL DRAFT**
**prEN 1991-1-4**

January 2004

ICS 91.010.30

Will supersede ENV 1991-2-4:1995

English version

Eurocode 1: Actions on structures - General actions - Part 1-4:
Wind actions

# Main Design Methods



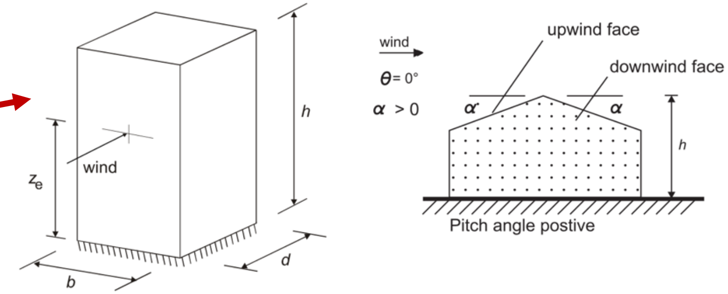
## STANDARDS & CODES

### Cons

- **Simplified Geometries Only**
  The Eurocode primarily addresses basic, regular-shaped structures. It does not adequately cover **complex geometries,** such as curved façades, high-rise buildings with irregular shapes, etc.

- **Standard Terrain Categories**
  The terrain exposure categories are overly simplistic and may not accurately represent **urban environments** with varying building densities, topography, or vegetation.

- **Limited Guidance on Local Effects**
  Effects like **channeling, vortex shedding, flutter and wake interactions** are not well addressed.



Eurocode 1-4


# Main Design Methods



EXPERIMENTAL

**FIELD MEASUREMENTS**

+ Real-world, high-fidelity data
+ Long-term monitoring
+ No scaling issues
− Low spatial resolution of the measuring points
− Difficult to control

**WIND TUNNEL**

+ **Stand alone tool!**

Well-established, controlled and repeatable

− Low spatial resolution of the measuring points

− Scaling issues

NUMERICAL

**CFD**

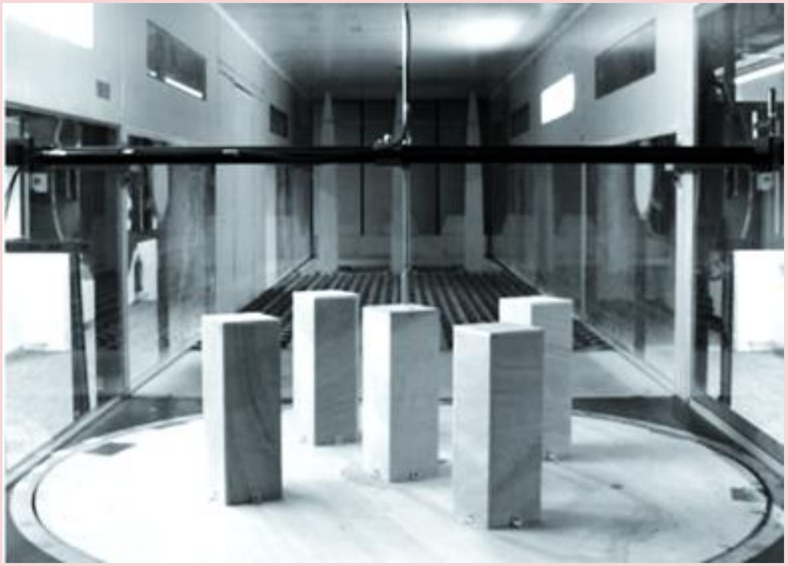
+ Flexible & scalable
+ Captures detailed flow around complex geometries
+ Ideal for parametric studies
− Sensitive to input (e.g. inflow) conditions
− **Needs validation!**

# Main Design Methods



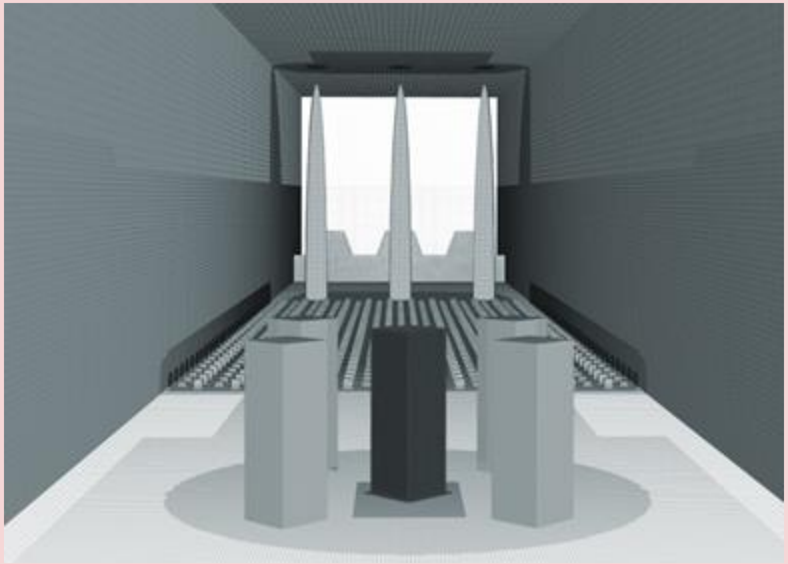
Where are we now?

**WIND TUNNEL**



VALIDATION

**CFD**



+ **Well-established, controlled and repeatable**
– Low spatial resolution of the measuring points
– Scaling issues

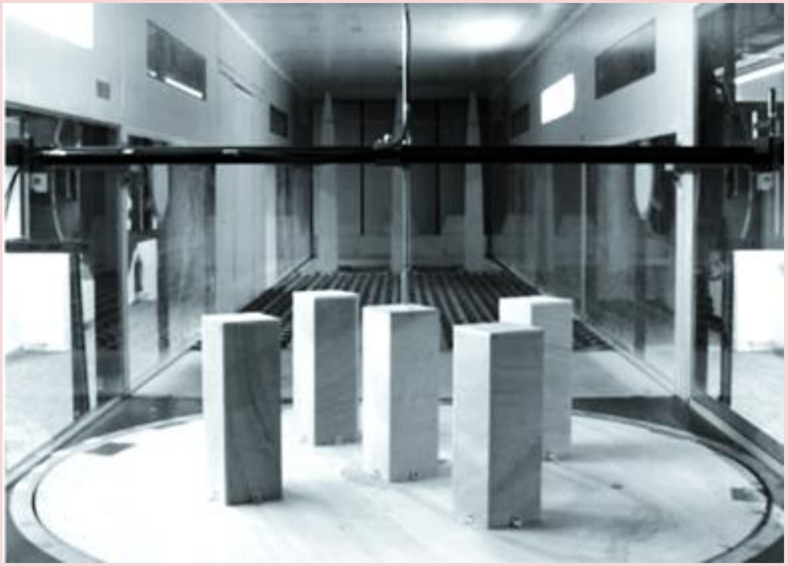
+ **Flexible & scalable**
+ **Captures detailed flow around complex geometries**
+ **Ideal for parametric studies**
– Sensitive to input (e.g. inflow) conditions
– Needs validation!

# Main Design Methods



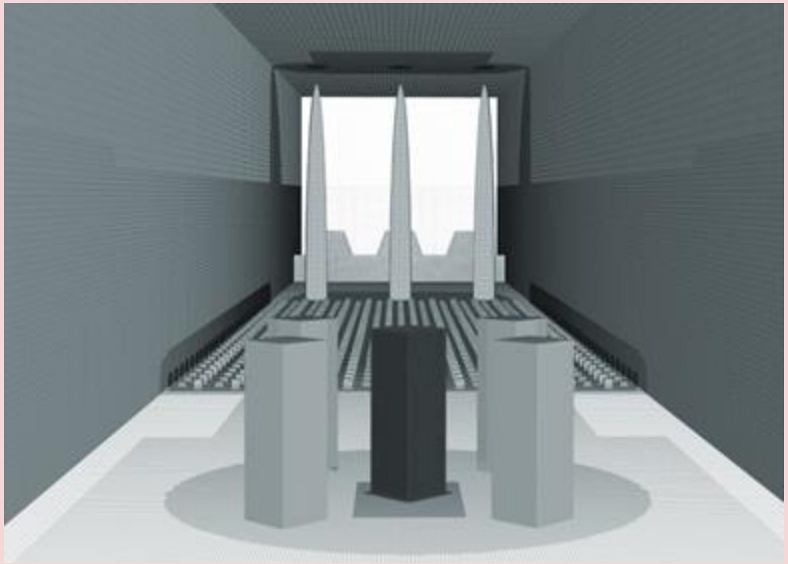
## WIND LOADS

### WIND TUNNEL



VALIDATION

### CFD



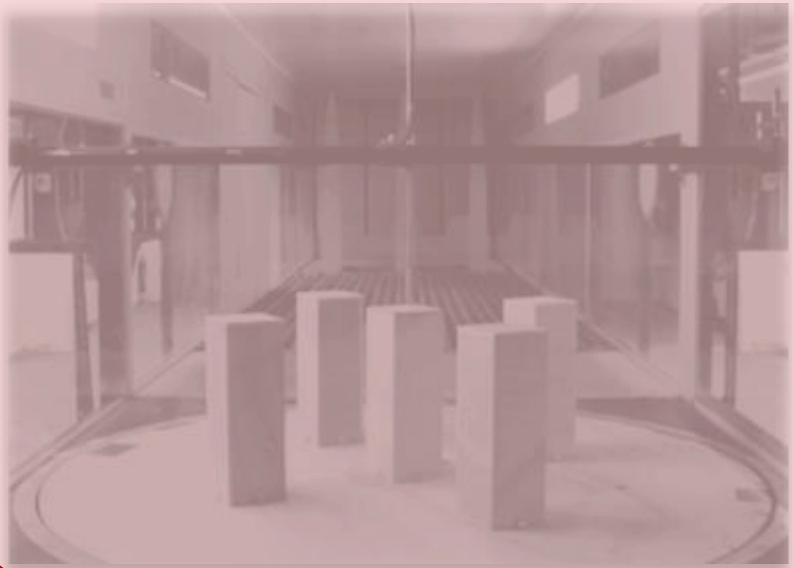
Each method plays a distinct role. WT & CFD used together, form a powerful tool for understanding and designing with wind.

# Main Design Methods



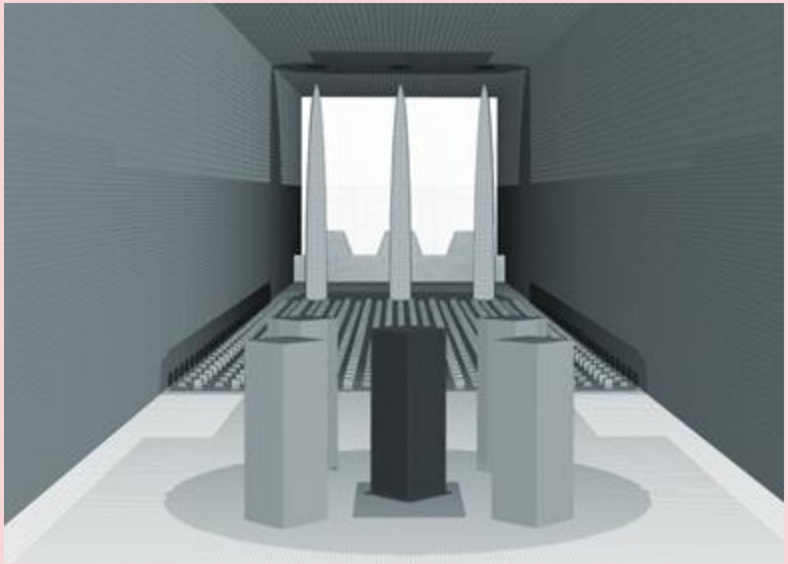
## ENVIRONMENTAL STUDIES

### WIND TUNNEL



VALIDATION

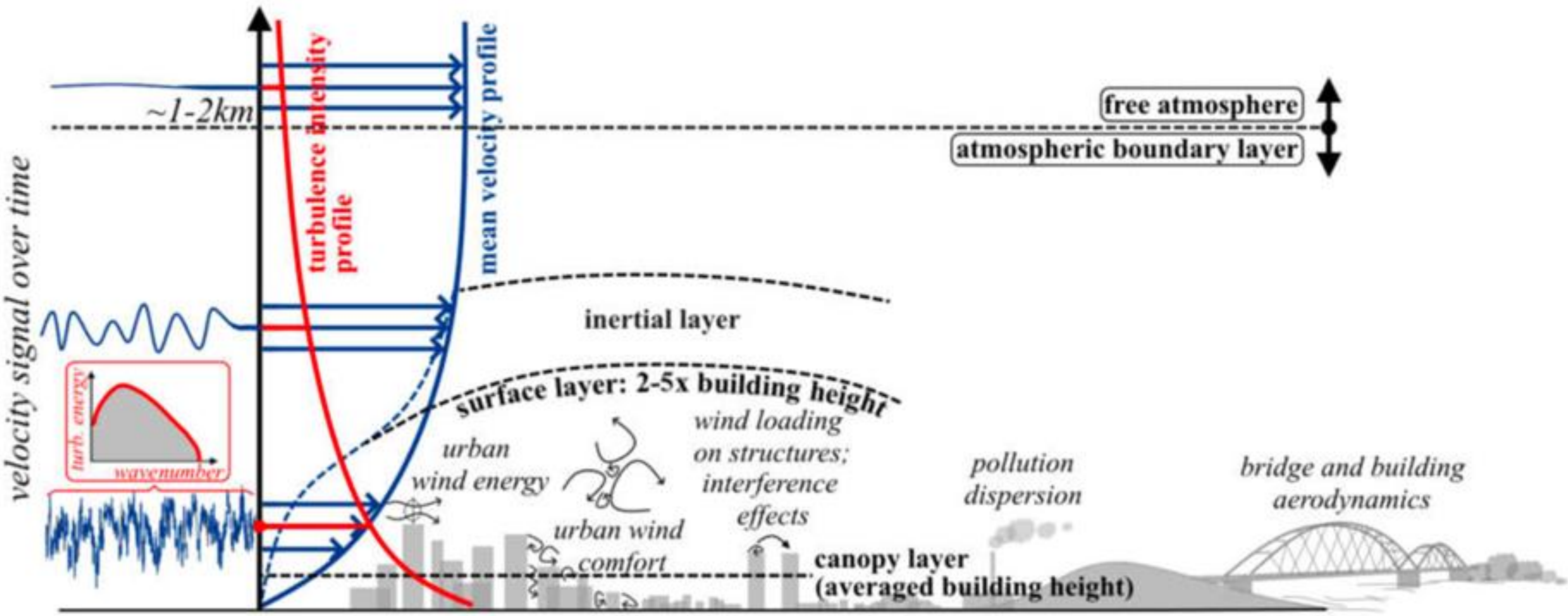
### CFD



# How we handle turbulence numerically?



**Approaching Flow - Atmospheric Boundary Layer (ABL)**




*Kostadinovic Vranesevic, University of Belgrade, 2025*

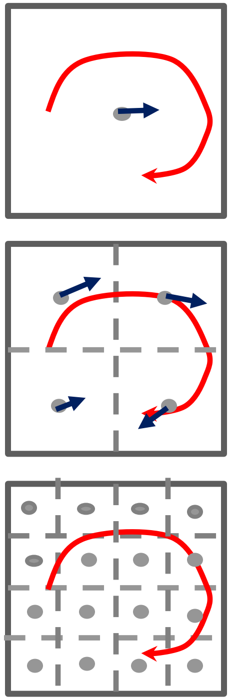
# How we handle turbulence numerically?

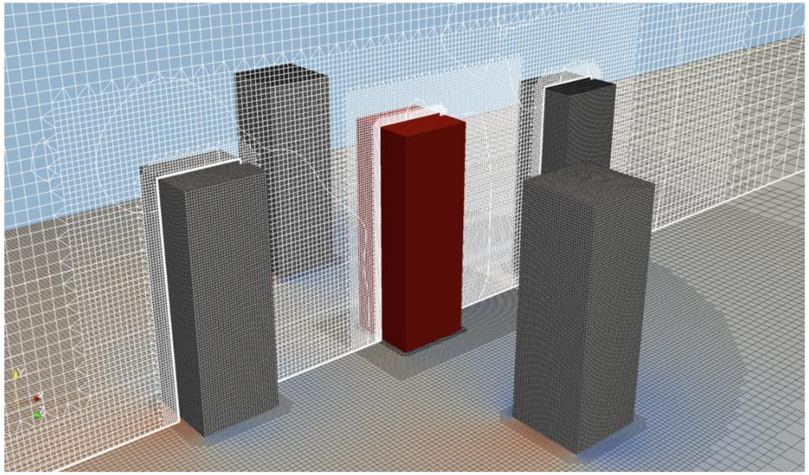


## Discretization of Navier-Stokes Equations

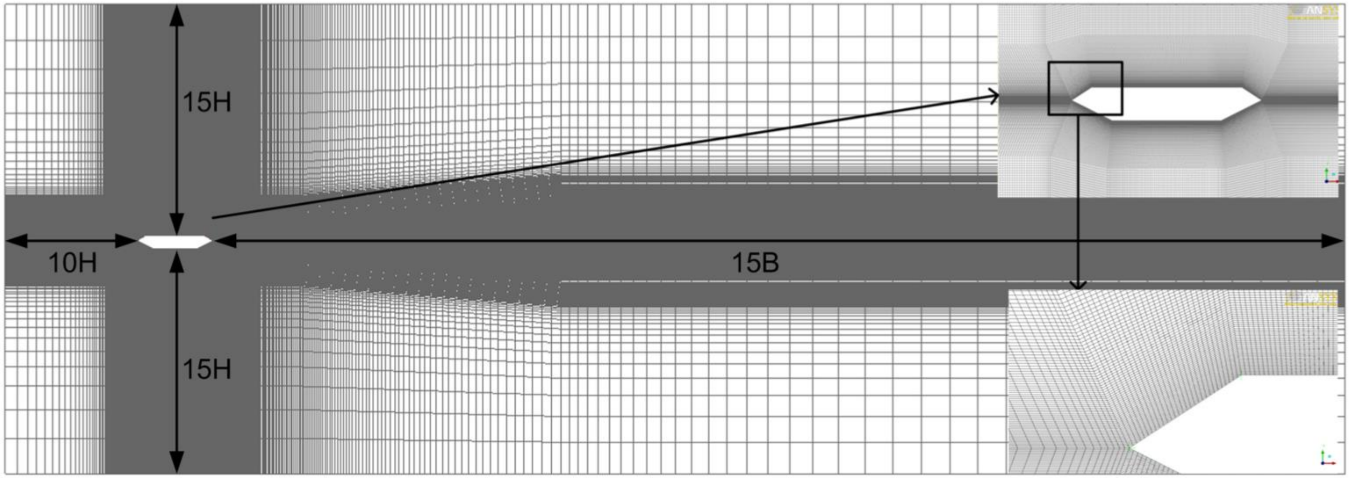
$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \nu \frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$





**Number of cells: 10x10⁶**

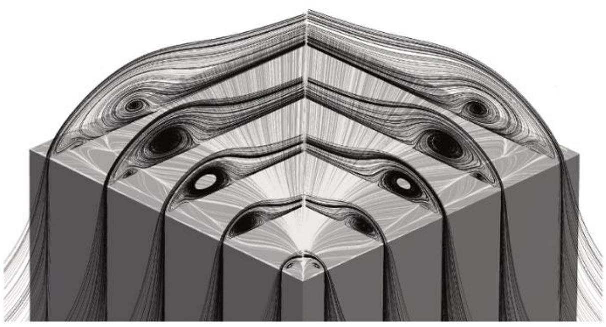


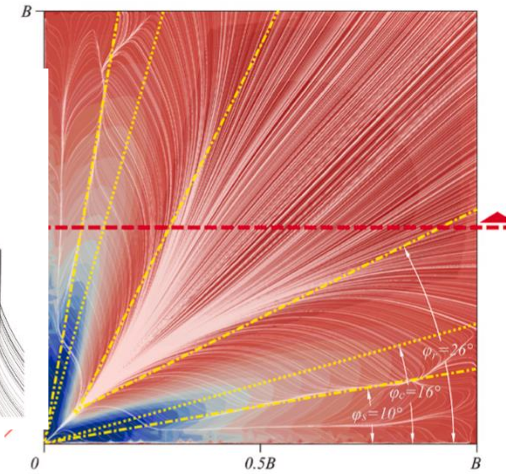

**Number of cells: 1,2x10⁶**

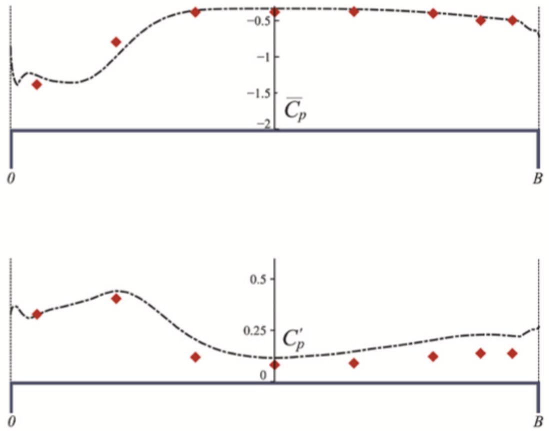
# Why such level of resolution?



**Complex flow**






**Flow** ⟷ **Pressures/Forces**

# Main QoI for Assessing the Wind Loads?

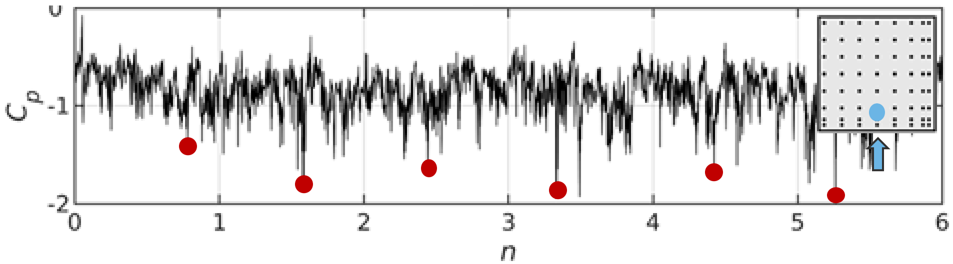


## Pressure Coefficients & Forces

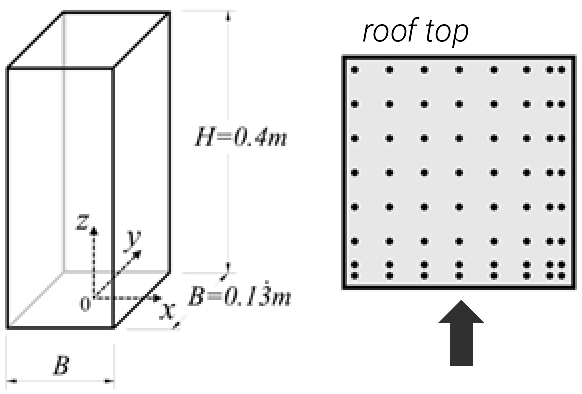
$$C_p^{\text{mean}} = \frac{\overline{p} - p_{\text{ref}}}{\frac{1}{2}\rho U_{\text{ref}}^2}$$

$$C_p^{\text{rms}} = \frac{\sqrt{\overline{(p - \overline{p})^2}}}{\frac{1}{2}\rho U_{\text{ref}}^2}$$

$$C_p^{\text{peak}} = \frac{p_{\max} - p_{\text{ref}}}{\frac{1}{2}\rho U_{\text{ref}}^2} \qquad C_p^{\text{peak}} = \frac{p_{\min} - p_{\text{ref}}}{\frac{1}{2}\rho U_{\text{ref}}^2}$$




## Loads on Structures

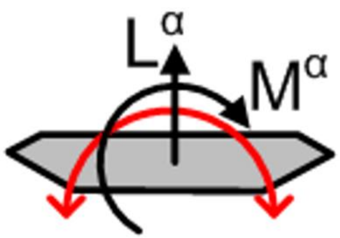



## … Aeroelastic Forces

$$L^{\alpha}(K) = \frac{1}{2}\rho K^2 U^2 B \hat{\alpha}\left[H_3^*(K) + iH_2^*(K)\right]$$

$$M^{\alpha}(K) = \frac{1}{2}\rho K^2 U^2 B^2 \hat{\alpha}\left[A_3^*(K) + iA_2^*(K)\right]$$

## Flutter in Bridges



# Main QoI for Assessing the Environmental Engineering Studies?

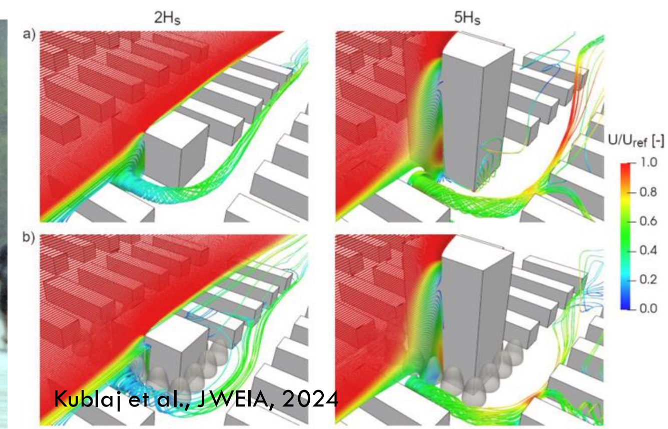


**Application Based**

- Velocities & Turbulence Intensities

Wind Microclimate Assessment and/or Optimisation

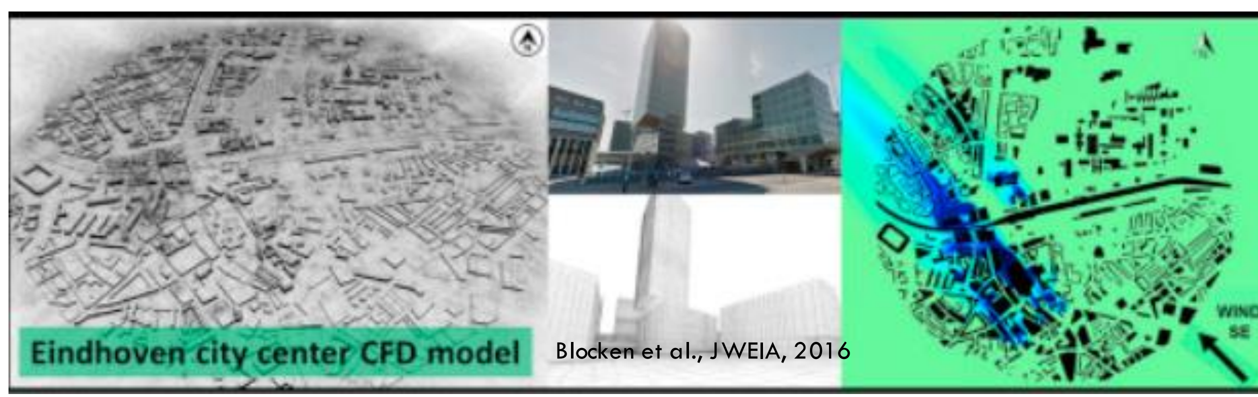
Pittsburg
Source: ...ost-gazette.co.../n..ws/weather-news/20...202303250072




Kublaj et al., JWEIA, 2024

- Pollutant concentrations, etc.

China,
Source: https://www.istockphoto.com/photo/china-shenzhen-skyscraper-gm969333552-264204925?searchscope=image%2Cfilm




Blocken et al., JWEIA, 2016

Pollution & Mitigation Studies

# How we handle turbulence numerically?



**Reynolds-Averaged Navier–Stokes**

**RANS**

+ Efficient estimates
– Steady state or Ensemble Averaged
– Lack of accuracy
– Low fidelity simulation

**Large Eddy Simulation**

**LES**

– High comp. costs
+ Transient response
+ Satisfactory accuracy
+ High fidelity simulation

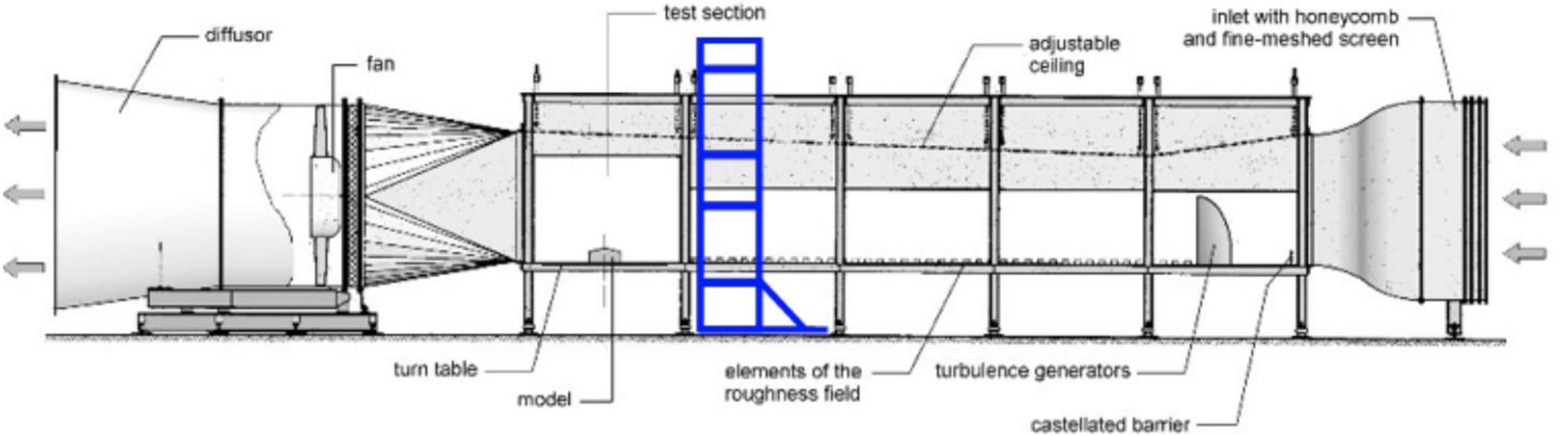
**How do we choose a CFD Approach?**

- Engineering Judgment & Experience
- Wind Load Studies – prefer LES if feasible
- Environmental Eng. Studies - RANS often sufficient

# Our Approach



## Wind Tunnel

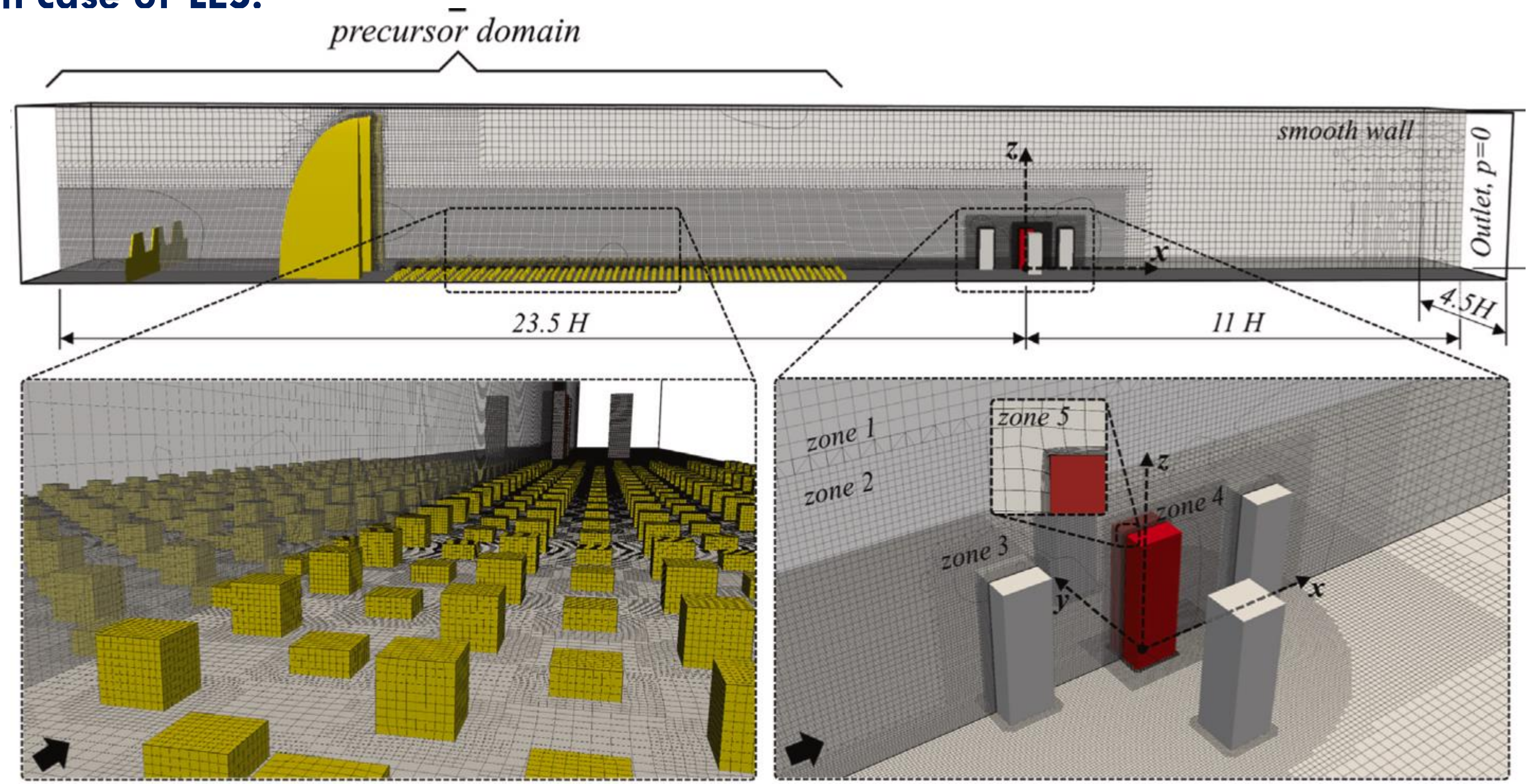


# Our Approach



## Virtual Wind Tunnel

**In case of LES:**

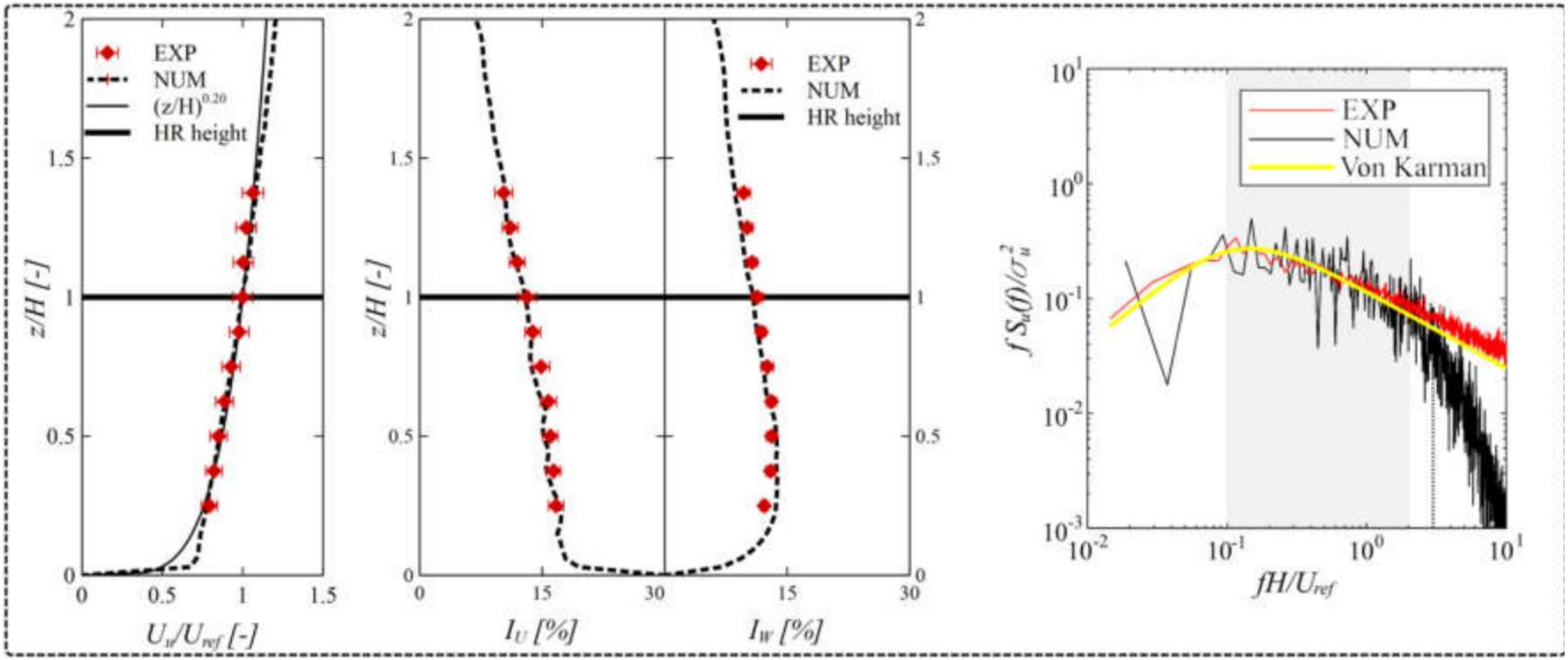


# Our Approach



**Virtual Wind Tunnel**

**ABL in case of LES:**



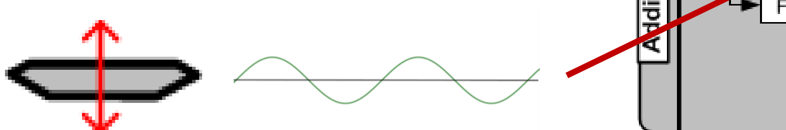
# Our Approach

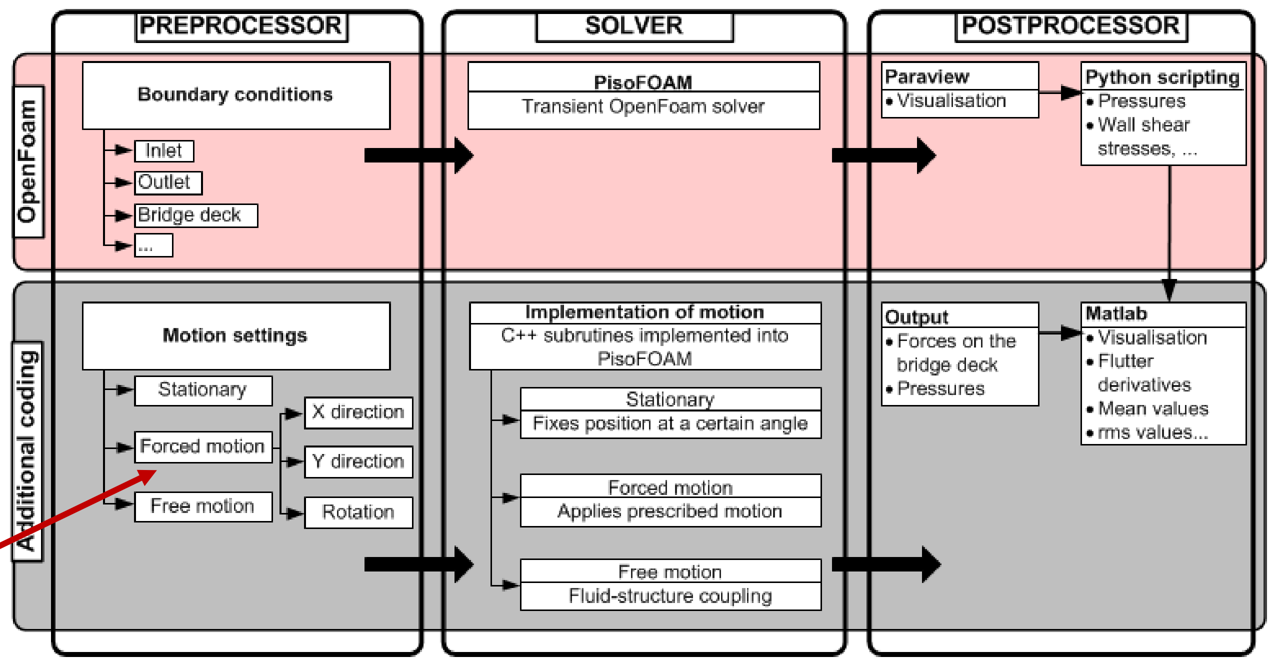


**Virtual Wind Tunnel**

**Bridge Aerodynamics** ⟶ **Specialized Experiments**

- Vortex Shedding
- Torsional Divergency
- Flutter, etc.

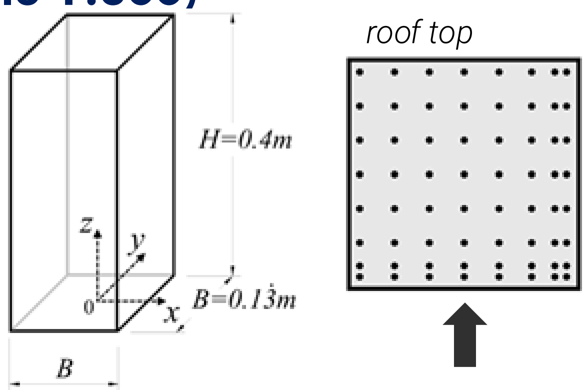


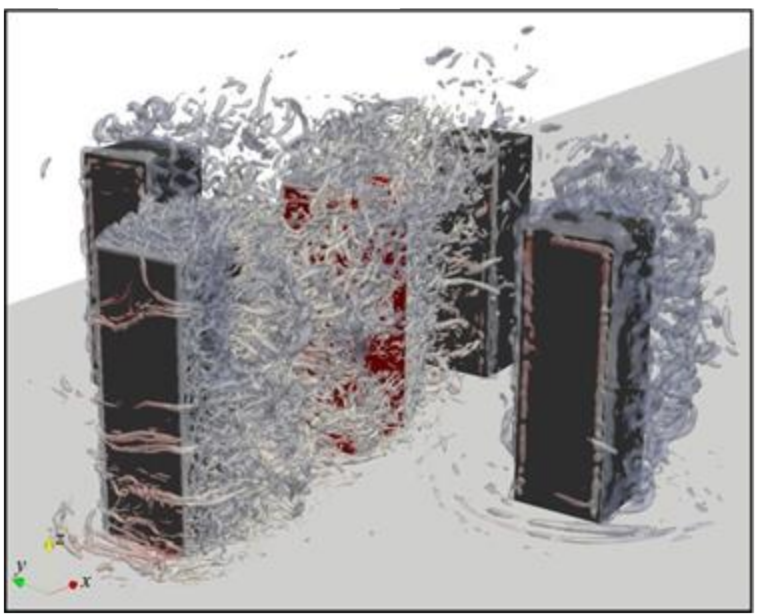


# High Rise building

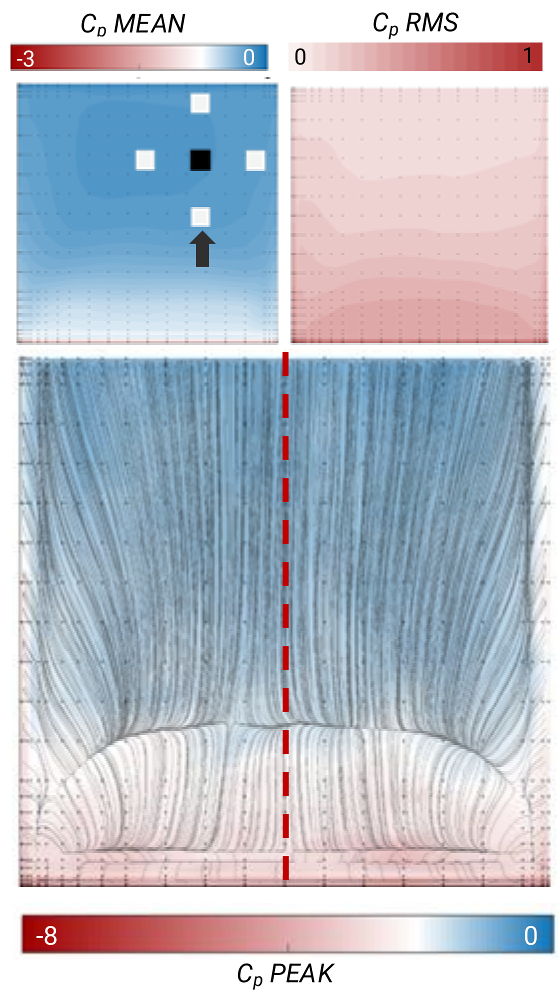


## Loads on the Roof Top (scale 1:300)

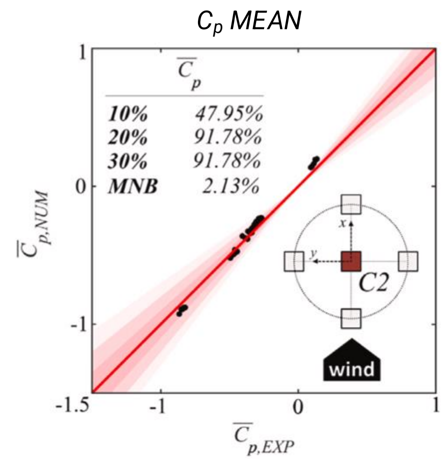


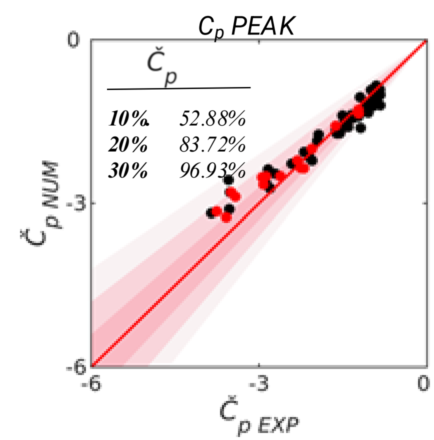



## LES Pressures - Roof Top




## LES vs Exp

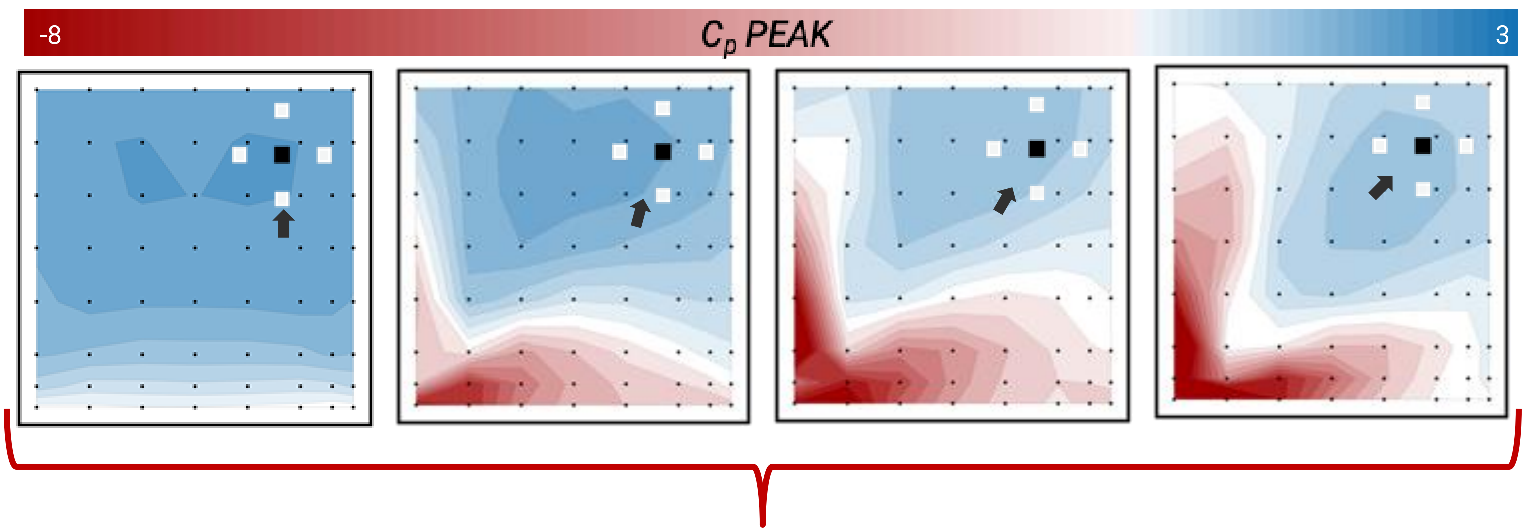


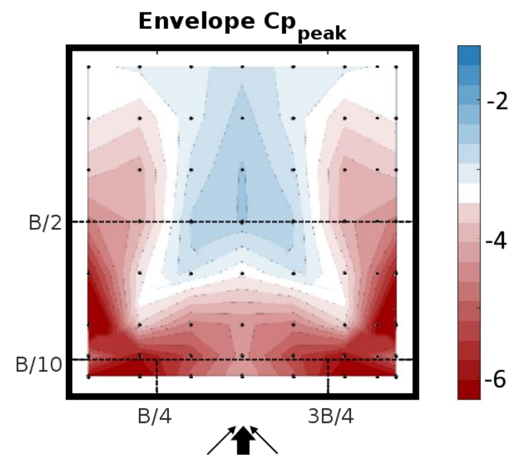



# High Rise building



## External Pressure Coefficients – Designed Values




**Whole Wind Rose!**

→ for each direction

– one simulation!

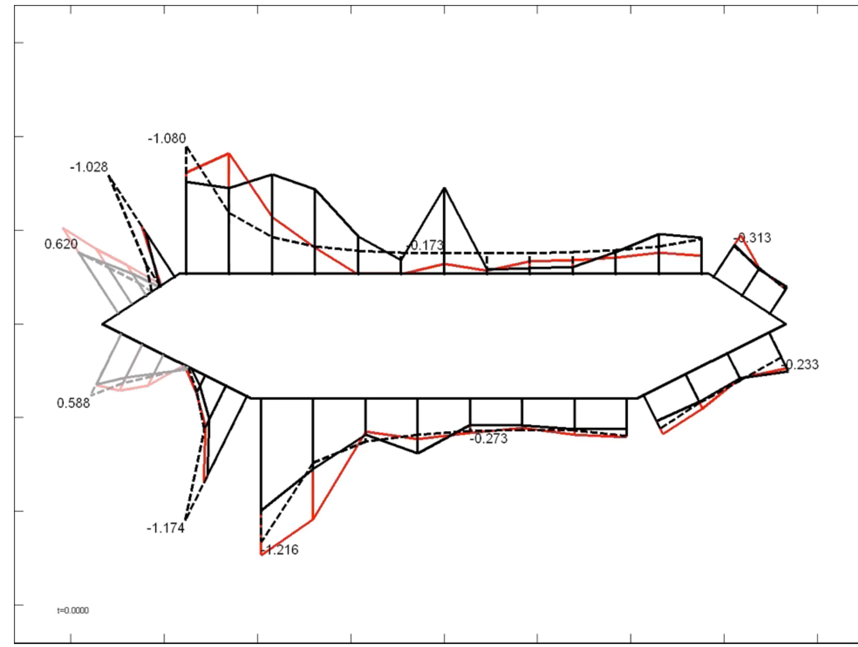
# Bridge Aerodynamics - Flutter



**Tacoma Narrows collapse 1940**


U

**Virtual WT vs Experiments**




U = 4.52 m/s
f = 3.02 Hz

A = 4 mm
$U_{red}$ = 4.09

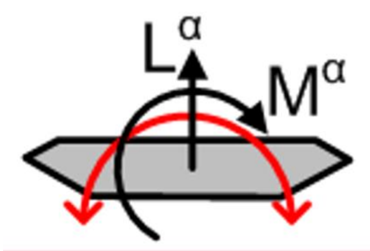
| | + | - |
|---|---|---|
| Measurement | + | - |
| LES | + | - |
| URANS | + | - |

*) ploted values related to URANS results

# Bridge Aerodynamics - Flutter

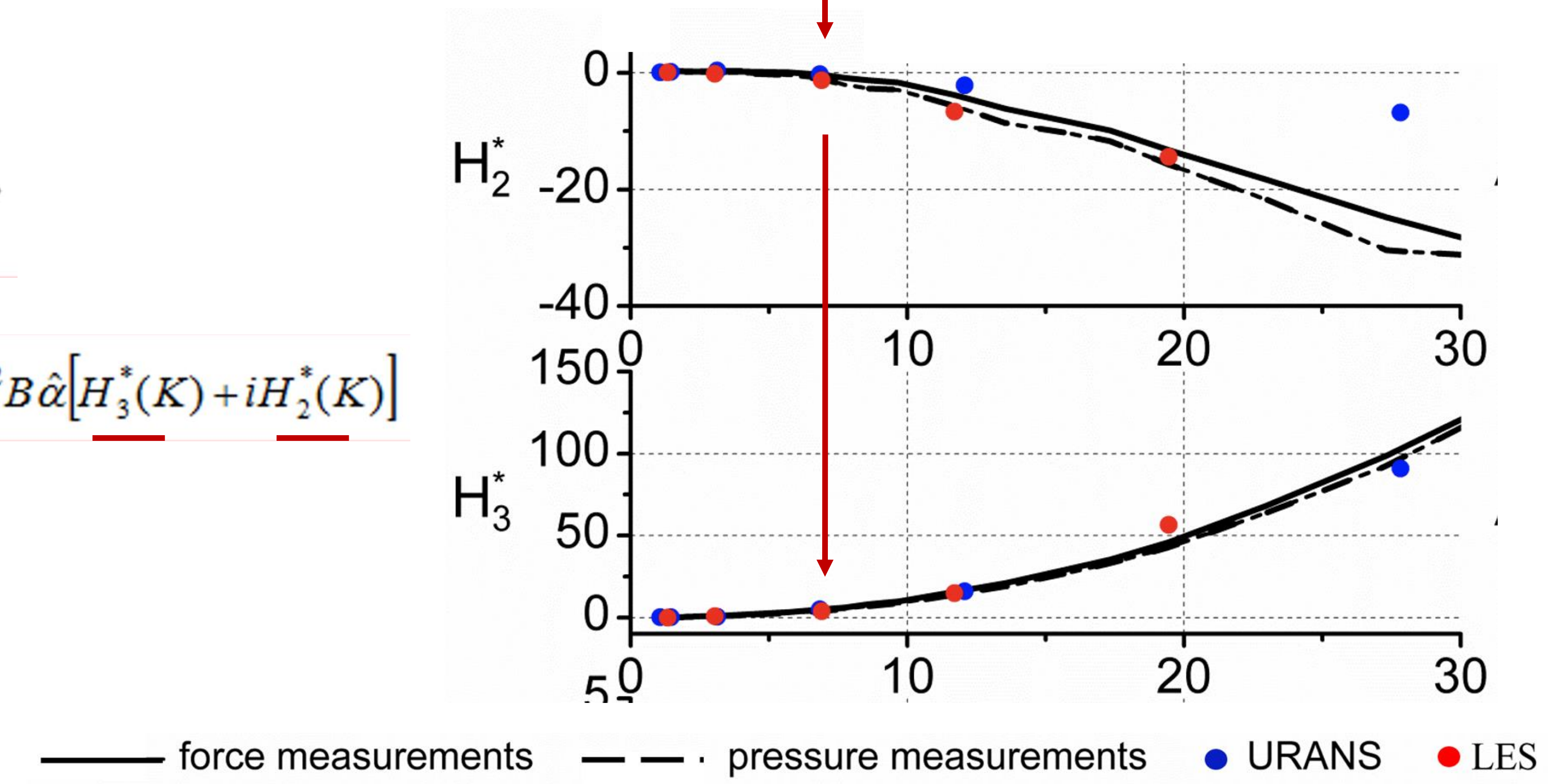


**Aeroelastic Lift Force**




$$L^{\alpha}(K) = \frac{1}{2}\rho K^2 U^2 B \hat{\alpha}\left[H_3^*(K) + iH_2^*(K)\right]$$

**One Simulation!**



# HPC Usage – Absolute Necessity!



### High – Rise Building Case

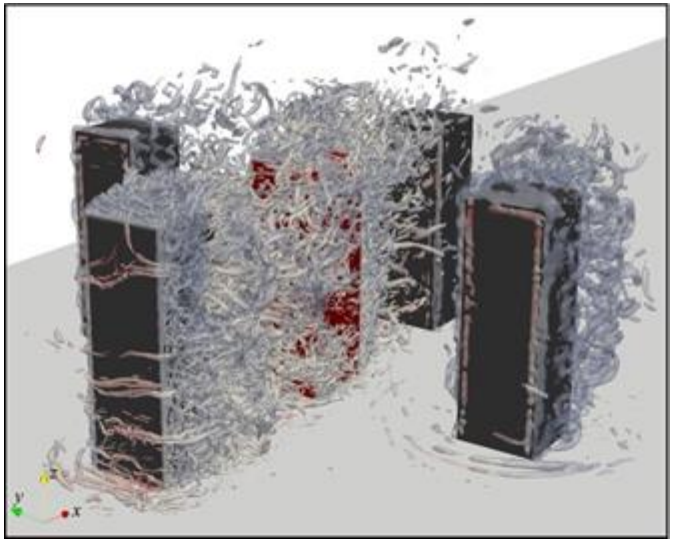
- Pre-calculation - Course Mesh:

$4{,}8 \times 10^6$ cells, 5575 CPUh

- Main Calculation - Fine Mesh:

$10 \times 10^6$ cells, 50000 CPUh

**→ for only one wind direction!**



### Bridge Case

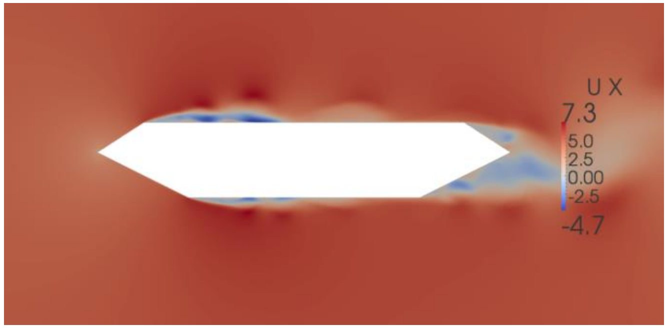
- Pre-calculation - Course Mesh:

$0{,}5 \times 10^6$ cells, 1300 CPUh

- Main Calculation - Fine Mesh:

$1{,}2 \times 10^6$ cells, 13440 CPUh

**→ for only one moving mesh case!**

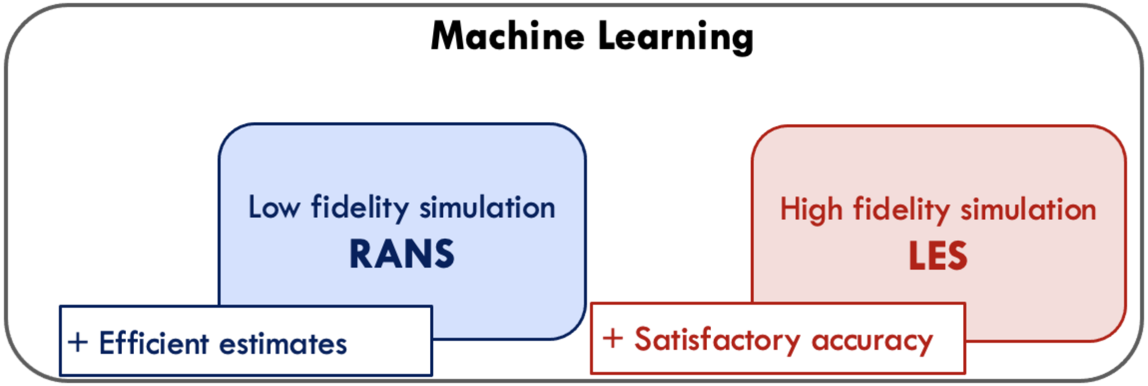


# Next Steps… – Machine Learning, Data Assimilation…



How to predict the urban wind flow patterns accurately but with a reasonable computational cost?

3 LES high-fidelity sim.
for 7 wind directions!

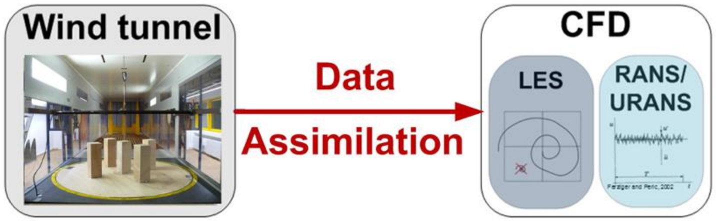



How can we use previous knowledge in diverse urban landscape (application in optimisation studies)?

Transfer Learning

How can we use knowledge from experiments (or high-fidelity sim.) to speed-up and enhance the simulations?

Data Assimilation



# Wind Engineering Group



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# THANK YOU!