Principal static wind loads within a rigorous methodology to the envelope reconstruction problem

Blaise Nicolas

University of Liège, ArGEnCo dept., Structural Engineering div.

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Liège, Belgium

Wind loads on buildings and structures

- Structures with usual shapes

House

Low-rise building

Middle-rise building

Wind loads on buildings and structures

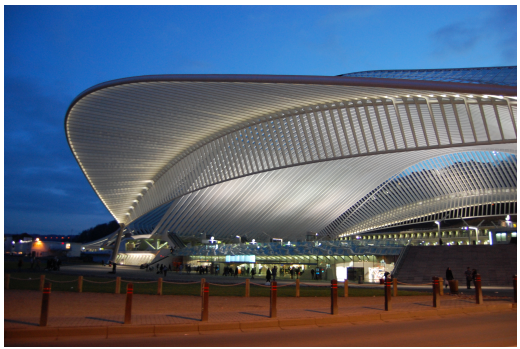
- Structures with usual shapes

House

Low-rise building

Middle-rise building

- Structures with unusual and even unique shapes

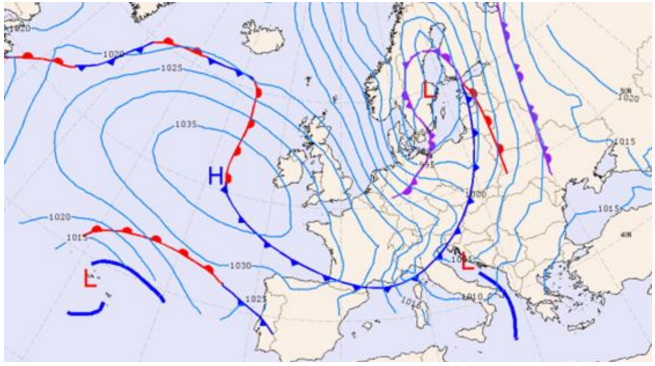


Gare des guillemins (198m×156m), Liège (Belgique)

Marseille's velodrome (105m×68m), France

Various wind systems

- Synoptic winds (considered in this work)
  - Stationary over the duration of the storm



- Non-synoptic winds (not considered in this work)
  - Transient phenomena

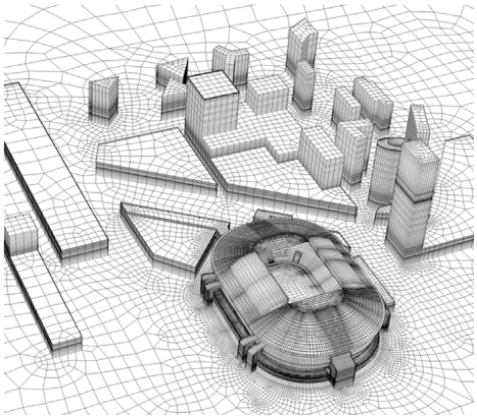
Downburst

Thunderstorm

Tornado

Characterization of the aerodynamic pressure field

- Computational Fluid Dynamics (CFD)



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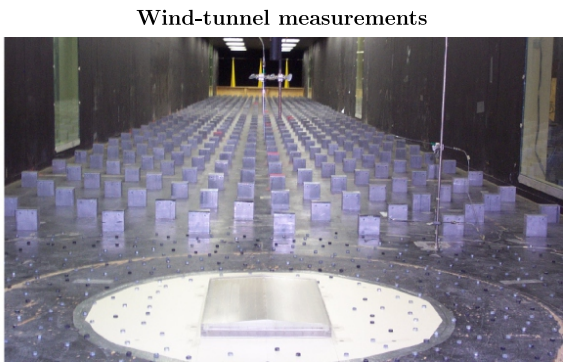
- Wind-Tunnel Testing



Boundary Layer Wind Tunnel Laboratory (BLWTL)
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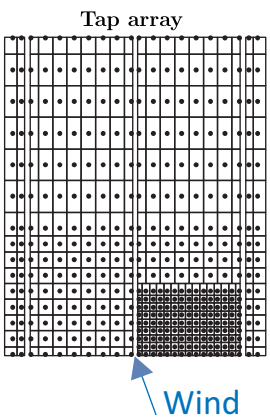
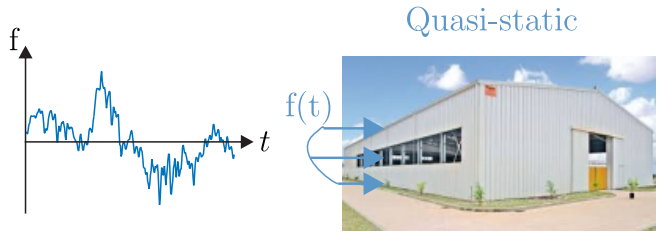


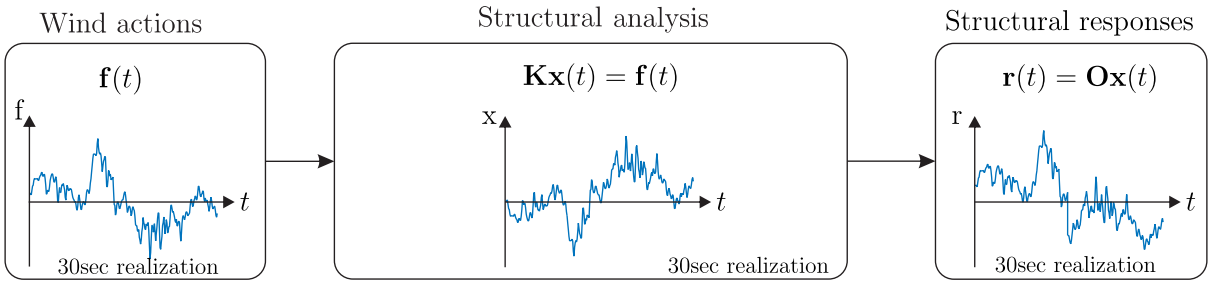
1 Van Hooff T., Blocken B (2010). Coupled urban wind flow and indoor natural ventilation modelling on a high-resolution grid: A case study for the Amsterdam ArenA stadium

Structural analysis

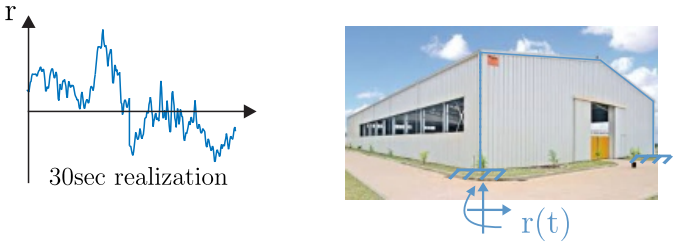
- Linear structural behavior



- Equation of motion



- Structural responses (displacements, internal forces, stresses,...)



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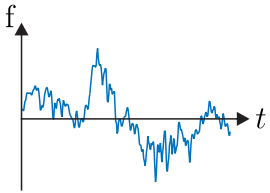
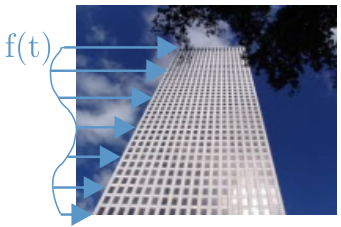


Quasi-static

Dynamic



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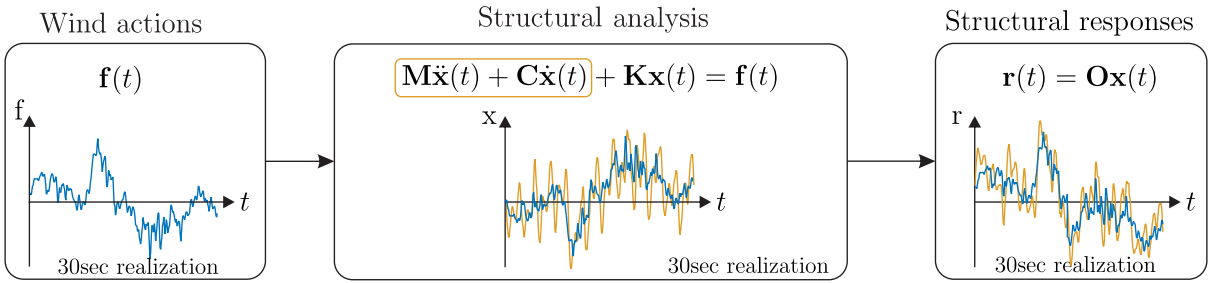

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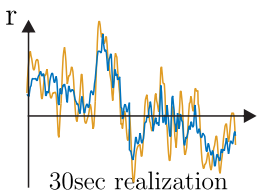
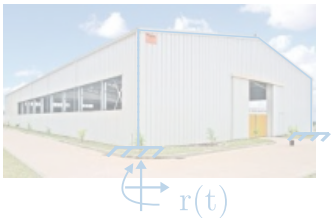
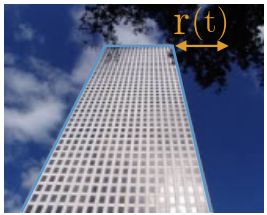
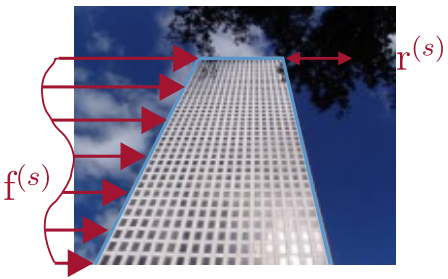


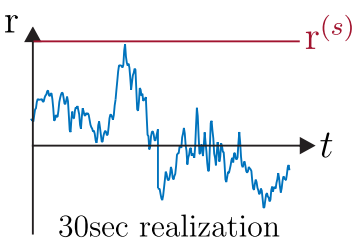


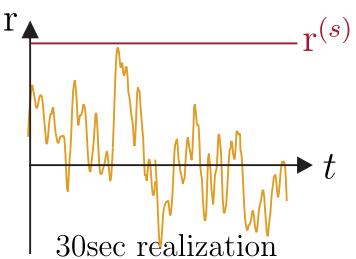


Equivalent static analyses

- Static load distributions: $\mathbf{f}^{(s)}$, Static analyses: $\mathbf{K}\mathbf{x}^{(s)} = \mathbf{f}^{(s)}$, Static responses: $\mathbf{r}^{(s)} = \mathbf{O}\mathbf{x}^{(s)}$







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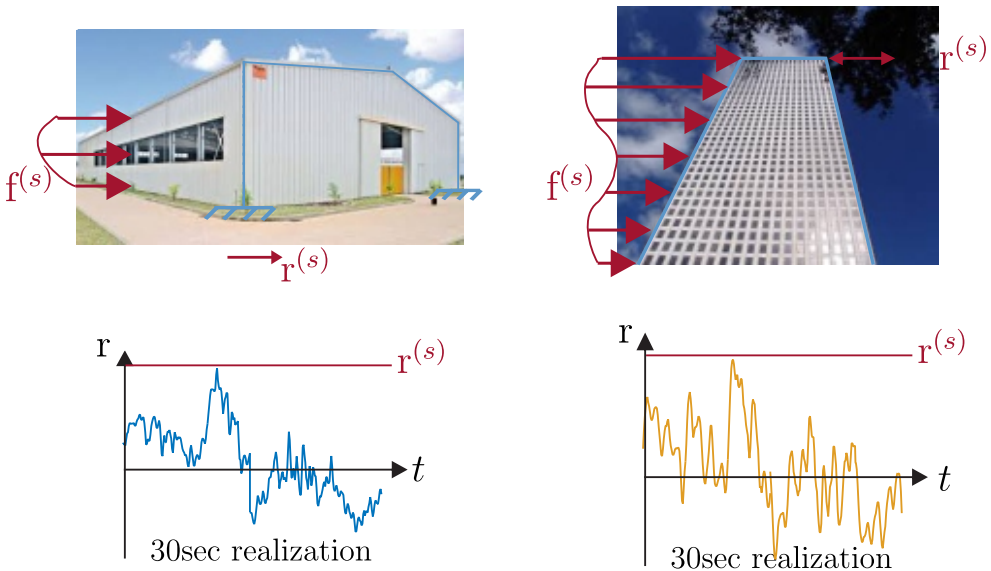

- Codified in standards
  - Usual structures: rectangular low-rise and middle-rise buildings, bridges, etc...
  - European committee for Standardization: Eurocode EN 1991-1-4:2005

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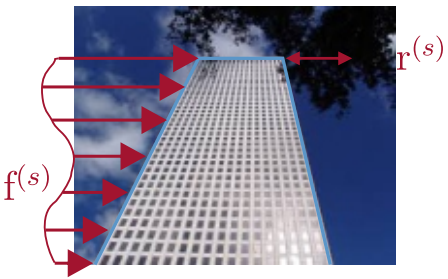

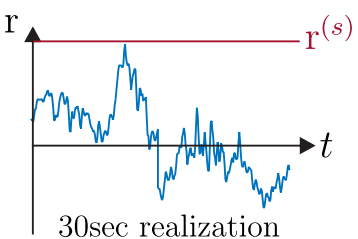

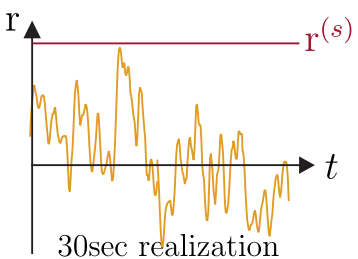

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- Structural dynamical analyses are cumbersome $\Longleftrightarrow$ Static analyses are straightforward

Motivation: large civil engineering structures

- Eurocodes
  - Civil engineering works up to **200** m
  - **Usual shapes** of buildings
  - Tower: vibrations in only the **fundamental mode**

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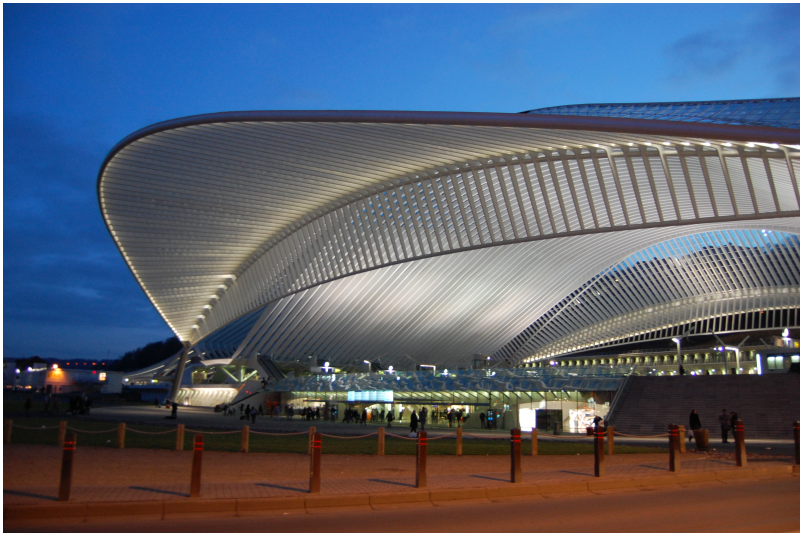

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Computed graphic of Marseille's velodrome (105m×68m), France

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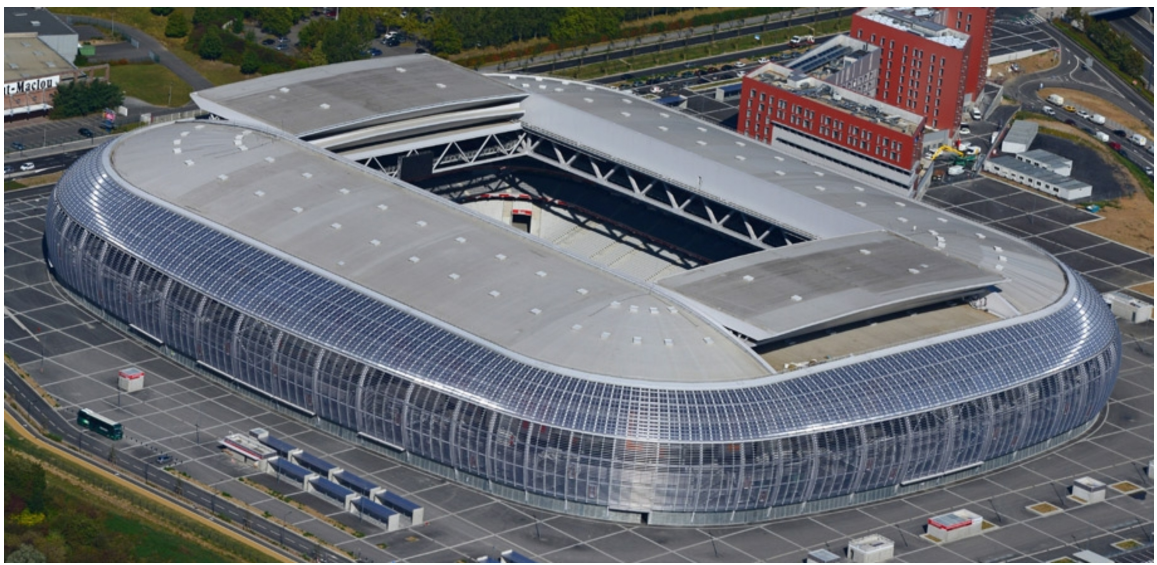
How to establish static wind loads for large (roof) structures?

Shenzhen Citizen Center (540m×282m,60m), China

Illustrations: two structures are studied

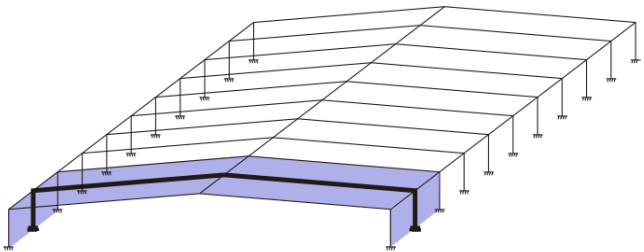
- Illustration: **Lille's stadium**
  - Dimensions: 230m×200m×36m
  - 50300 seats (UEFA 5⋆)
  - Retractable roof (7400 tons)



Stadium in Lille, France

Illustrations: two structures are studied

- Illustration: **An "academic" stiff gable roof building**



36.6m wide, 57.2m long, 3.65m eave high

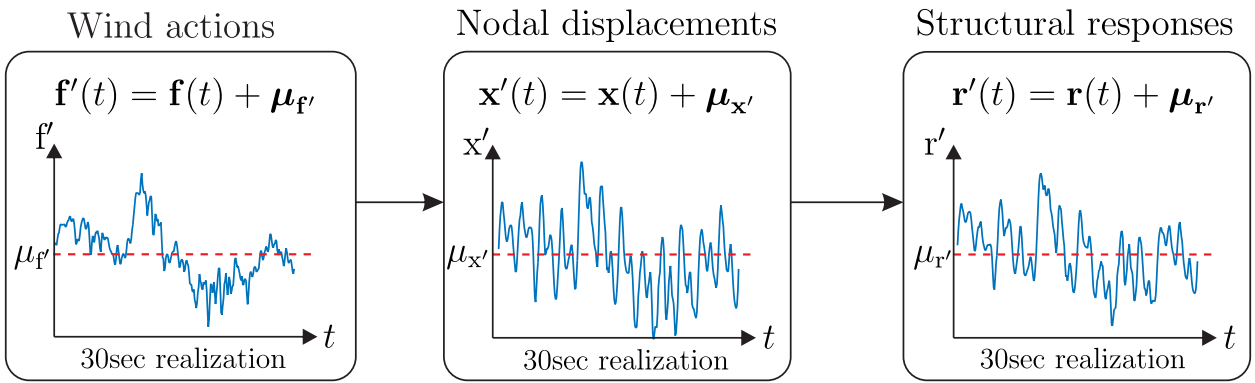
- Real-life example

Frisomat project[1] in Brazzaville, Congo (40m wide, 140m long, 11m high)

1 http://www.frisomat.be/en/News/In-Congo-Brazzaville–100-000m–of-pre-engineered-steel-buildings-.aspx

Theory of probability

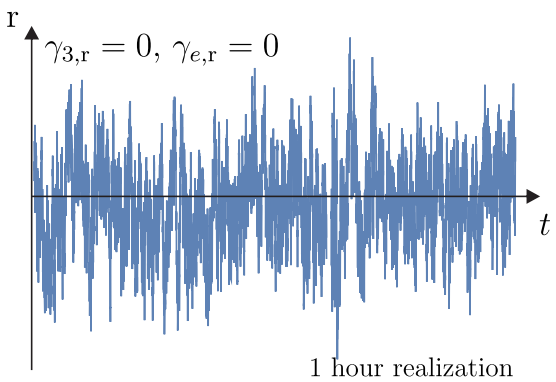
- Stationary random processes

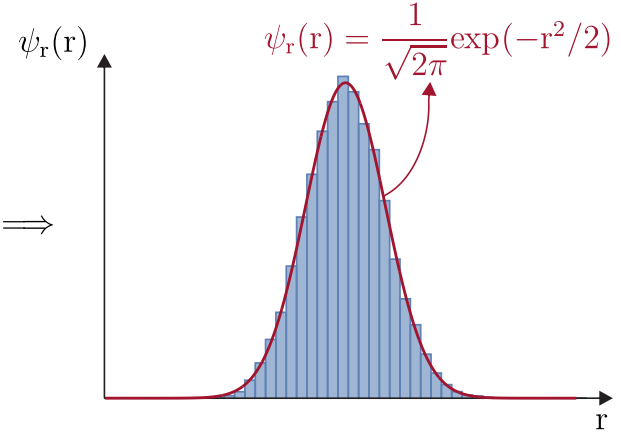


- Consequence: statistical moments are constant over time
  - $\mu_{\mathrm{r}'} = \mathbb{E}\left[\mathrm{r}'\right]$: Mean component
  - $\sigma_{\mathrm{r}} = \left(\mathbb{E}\left[\mathrm{r}\right]^2\right)^{0.5}$: Standard deviation
  - $\gamma_{3,\mathrm{r}} = \mathbb{E}\left[\mathrm{r}^3\right] / \sigma_{\mathrm{r}}^3$: Skewness coefficient (Gaussian $\gamma_{3,\mathrm{r}}$=0)
  - $\gamma_{e,\mathrm{r}} = \mathbb{E}\left[\mathrm{r}^4\right] / \sigma_{\mathrm{r}}^4 - 3$: Excess coefficient (Gaussian $\gamma_{e,\mathrm{r}}$=0)

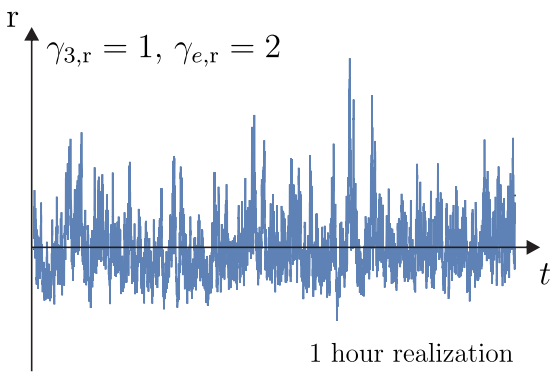
Probability Density Function (PDF)

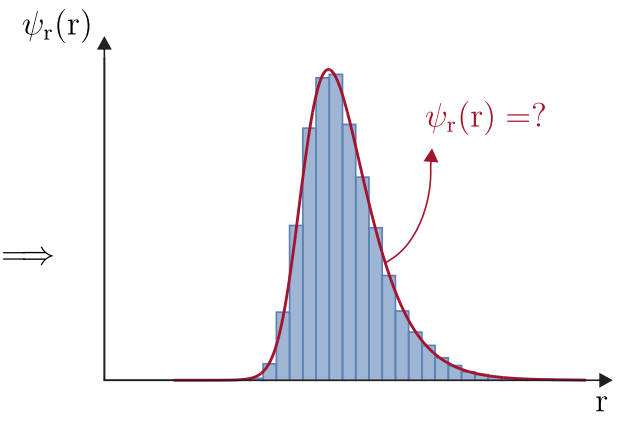
Gaussian random response





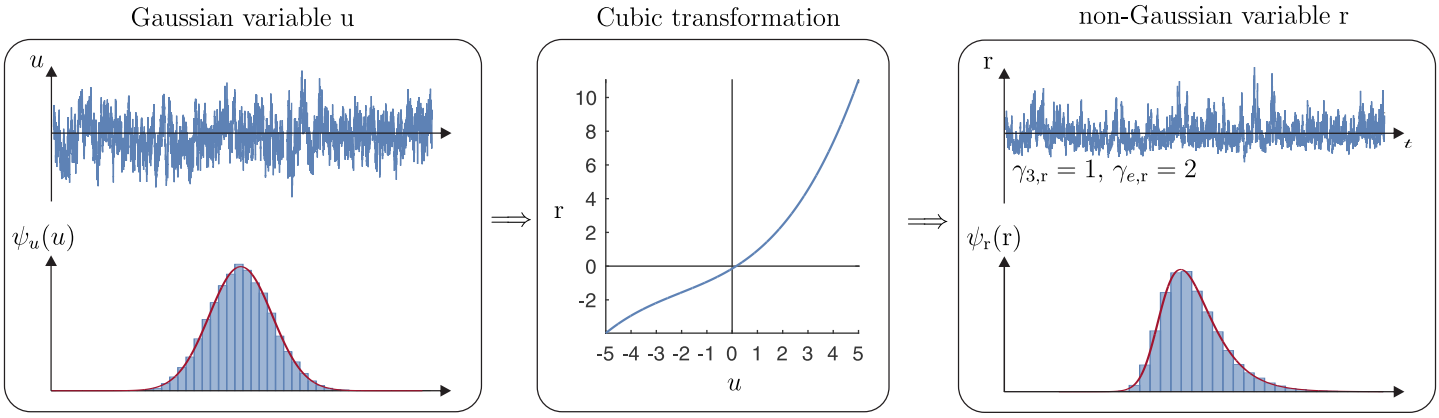
Non-Gaussian random response





Transformation of a Gaussian random variable

Hermite moment model



Cubic transformation

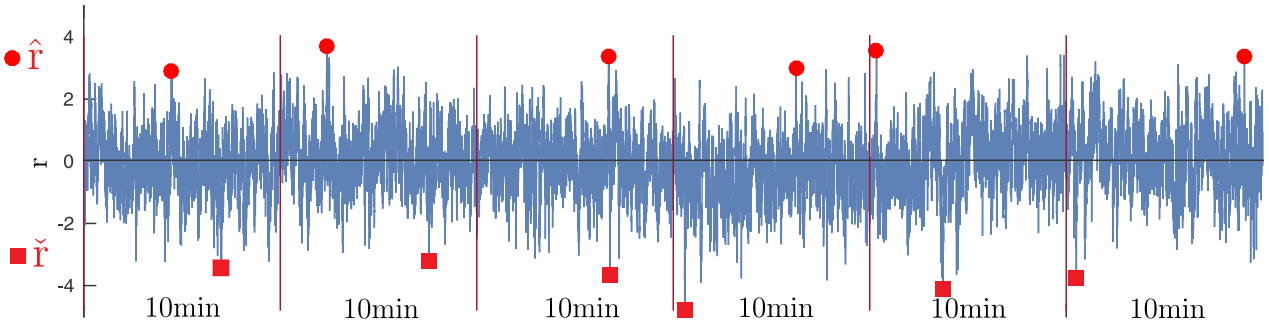
$$r = \frac{\alpha}{b}\left(\frac{u^3}{3} + au^2 + (b-1)u - a\right)$$

- 3-parameter (α, a, b) model
- Match the standard deviation σ_r, skewness $\gamma_{3,r}$ and excess $\gamma_{e,r}$ coefficients

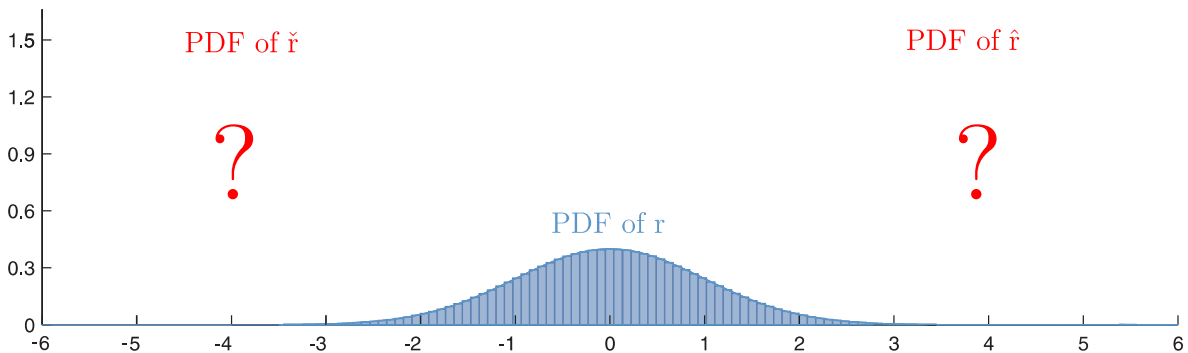
1 Winterstein, S. R. (1988). "Nonlinear vibration models for extremes and fatigue."

Extreme value theory (Gaussian framework)

- Duration of the storm: 10min



- Extreme values PDFs[1]



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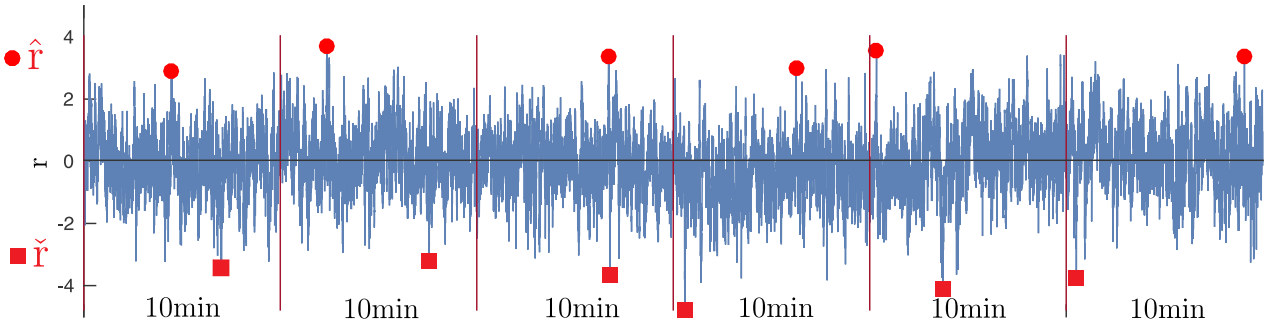

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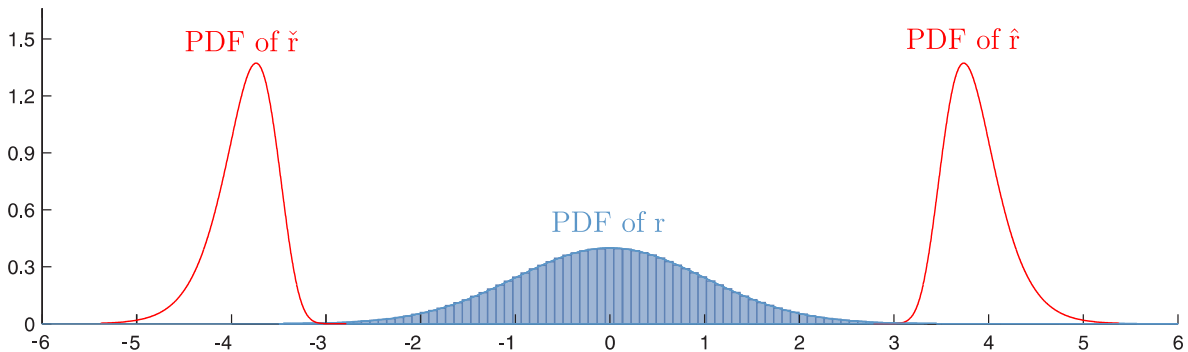

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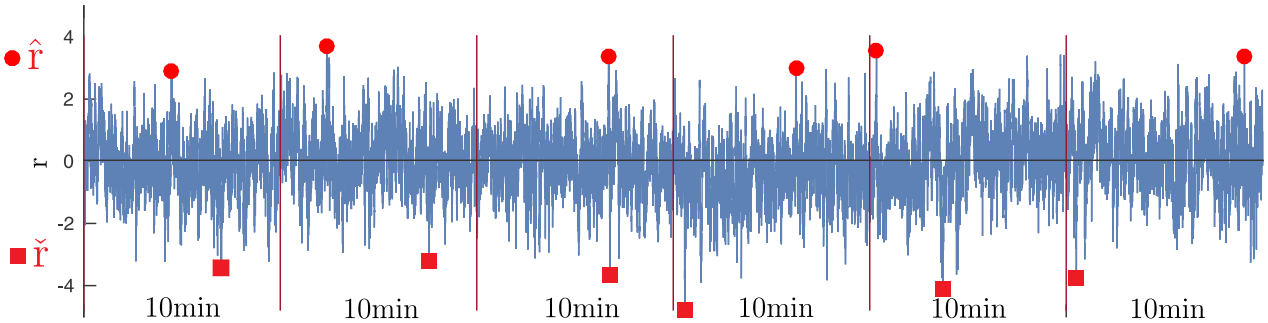

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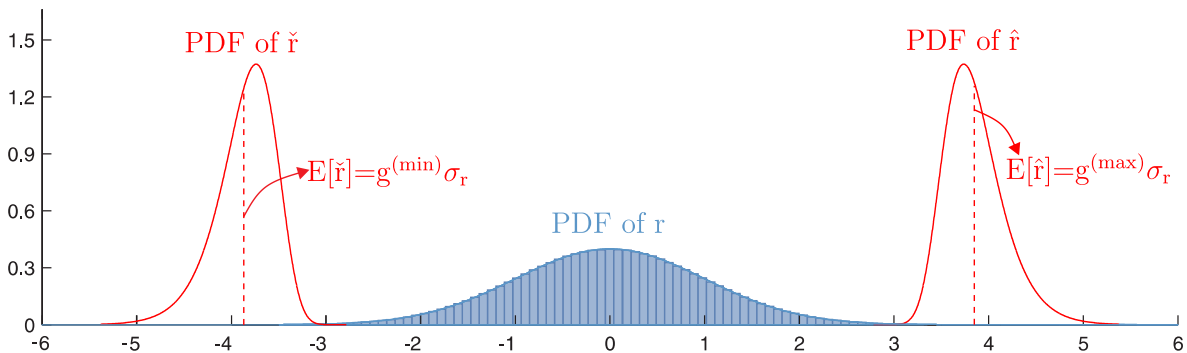
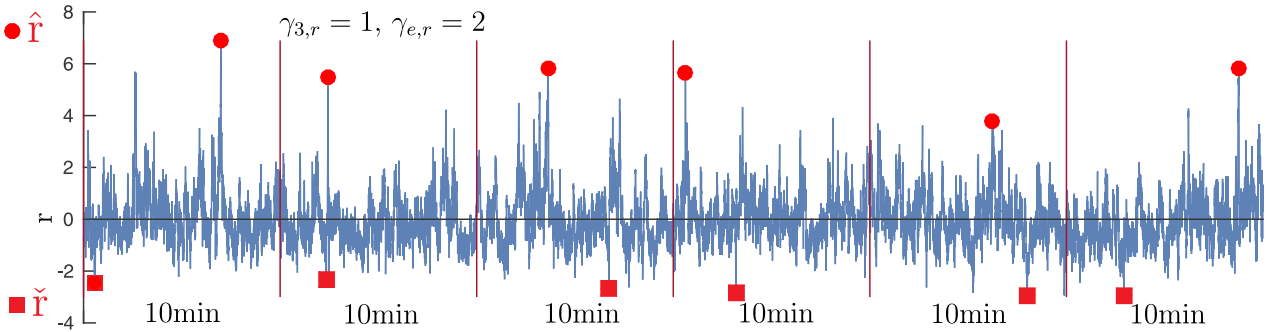


- Envelope values $\left(\mathrm{r}^{(\min)}, \mathrm{r}^{(\max)}\right)$ as mean values of the extremes $(\mathbb{E}[\check{\mathrm{r}}], \mathbb{E}[\hat{\mathrm{r}}])$
  - Davenport peak factors[1]: $\mathrm{g}^{(\max)} = -\mathrm{g}^{(\min)}$

1 Davenport, A. G. (1964). Note on the distribution of the largest value of a random function with application to gust loading

Extreme value theory (Non-Gaussian framework)

- Duration of the storm: 10min



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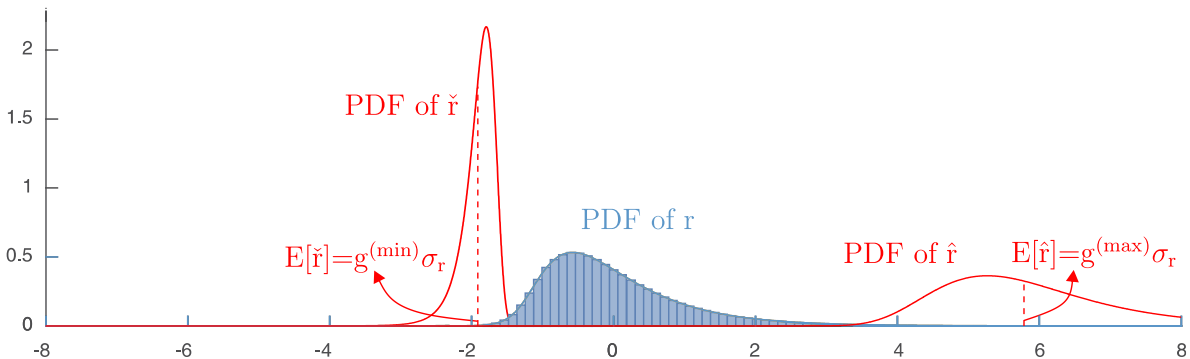

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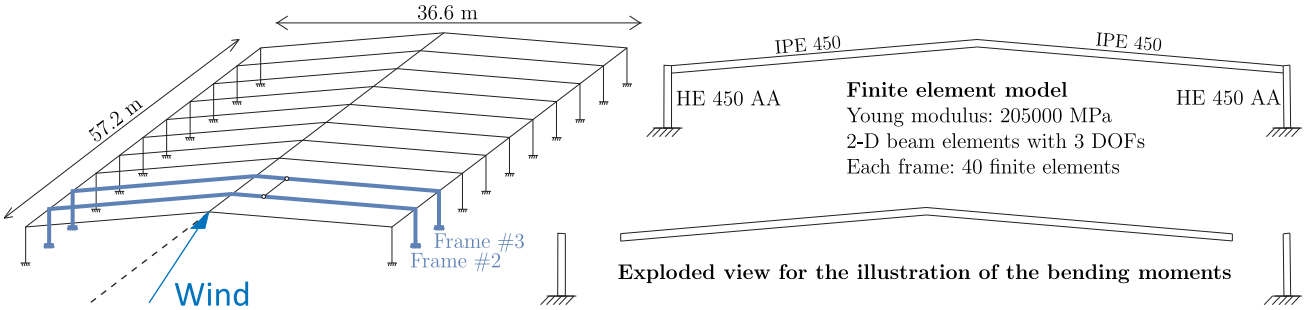
  - Kareem-Zhao peak factors[1]: $\mathrm{g}^{(\min)}$,$\mathrm{g}^{(\max)}$

1 Kareem, A. and J. Zhao (1994). "Analysis of Non-Gaussian Surge Response of Tension Leg Platforms Under Wind Loads."

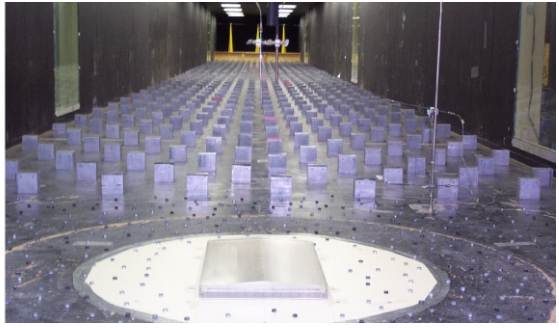
Illustration: Low-rise gable roof building

- Quasi-static non-Gaussian linear analysis
  - Structural responses: bending moments



- Non-Gaussian pressure field

Wind-tunnel measurements



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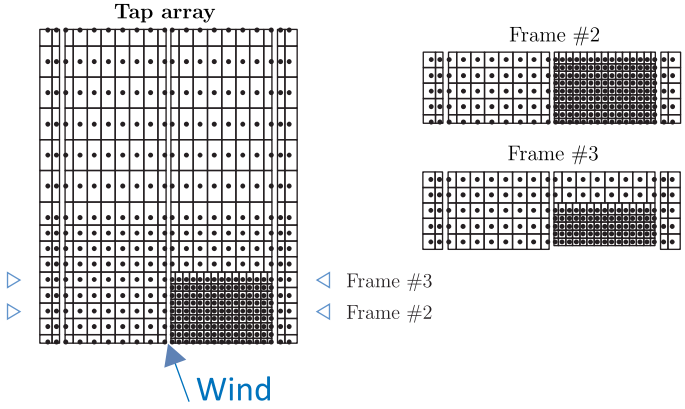
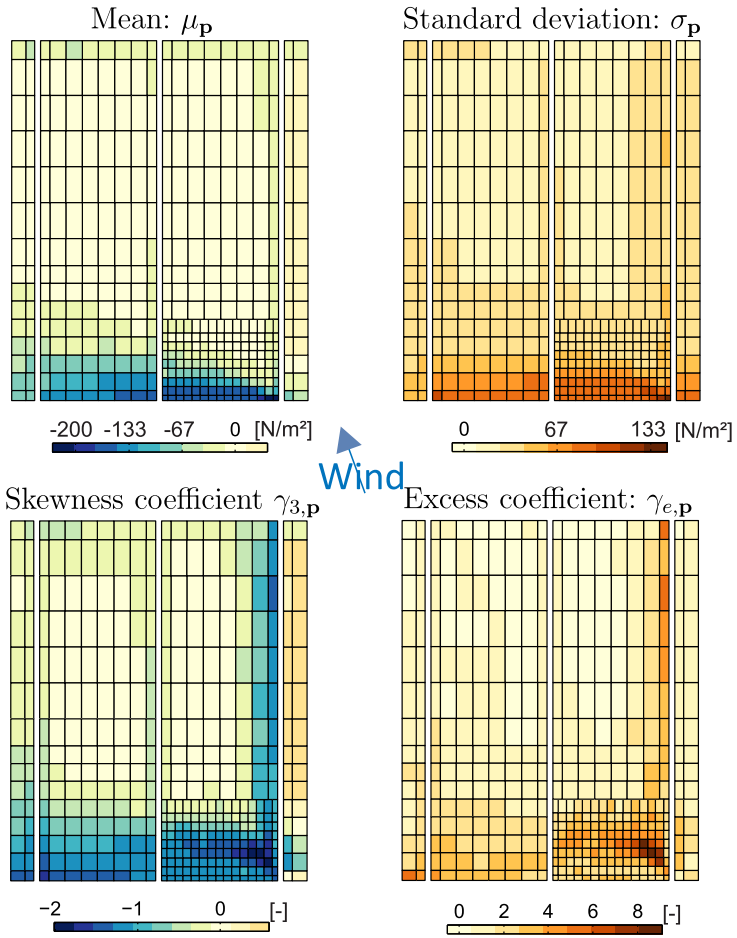


Illustration: Low-rise gable roof building

- Non-Gaussian aerodynamic pressure field



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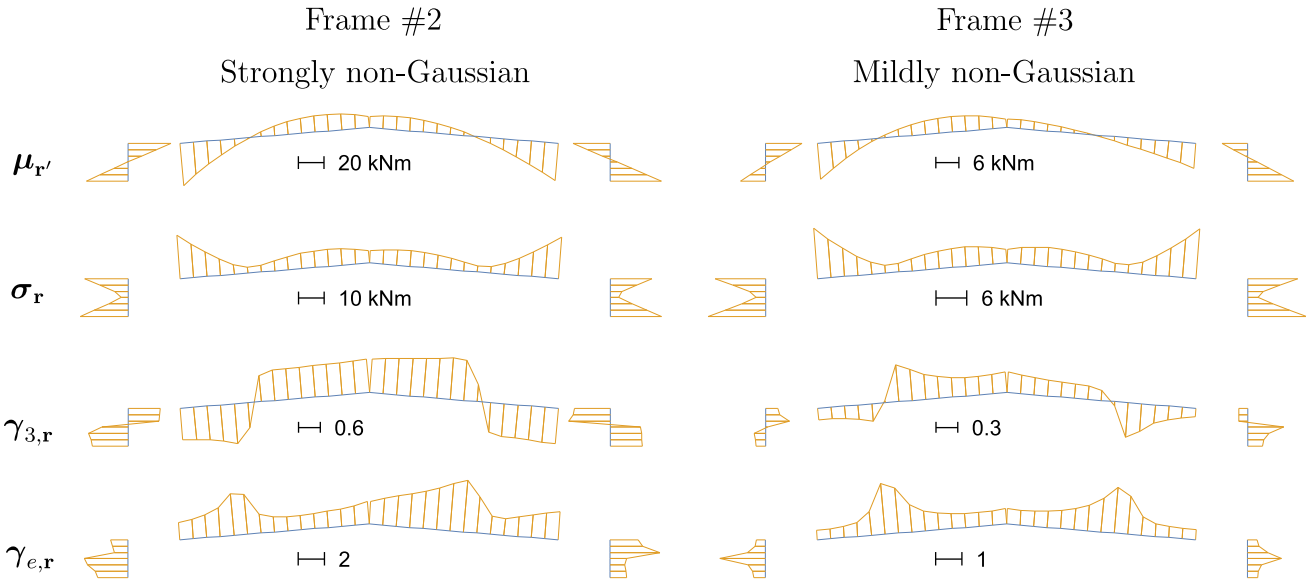
- Bending moments (non-Gaussian random responses)



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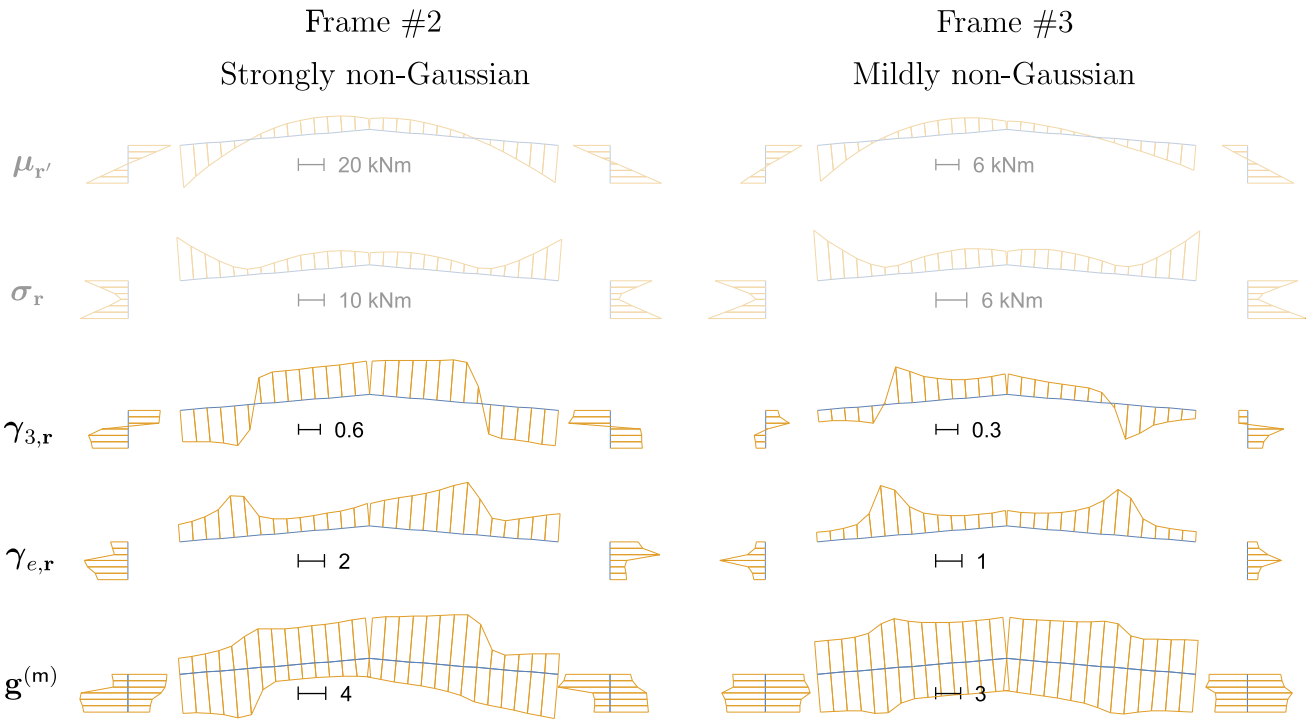

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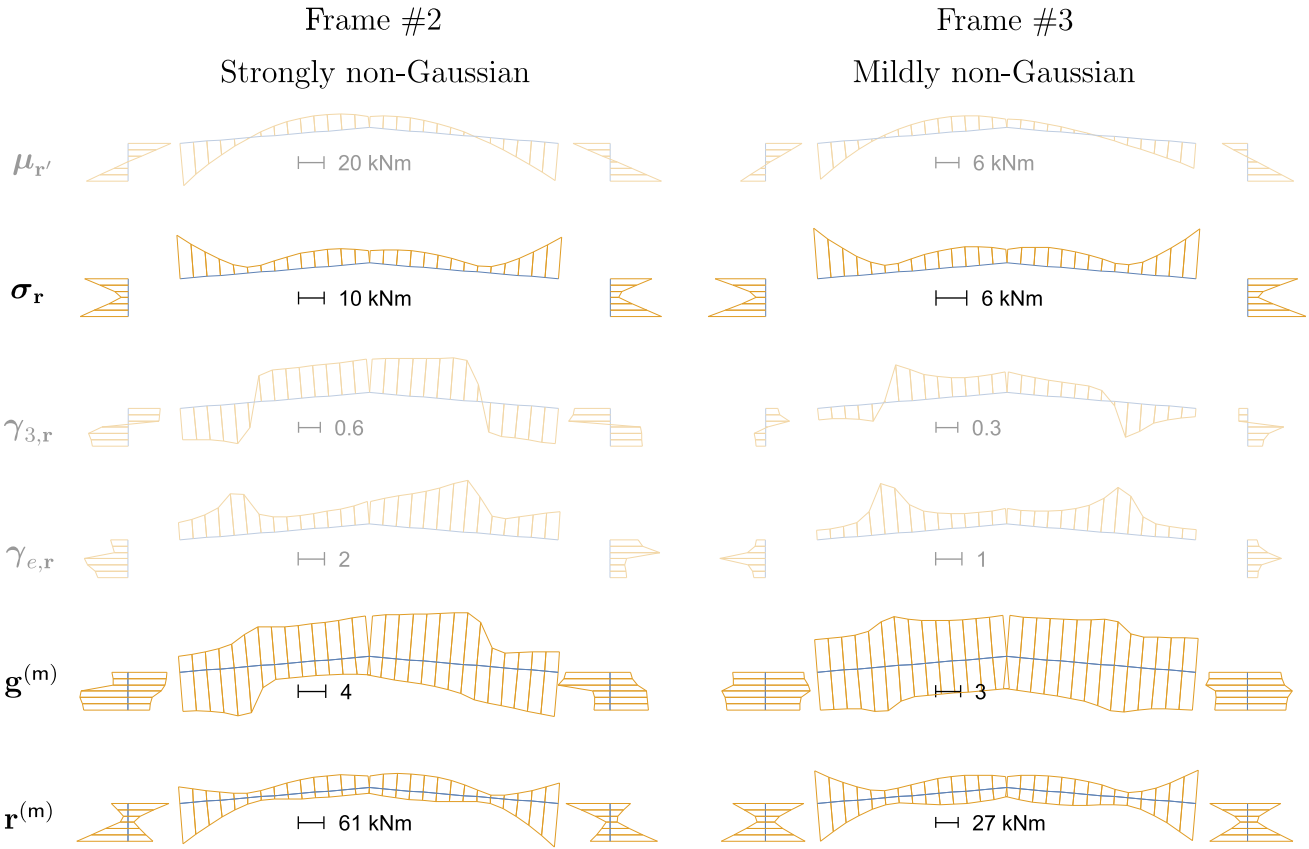
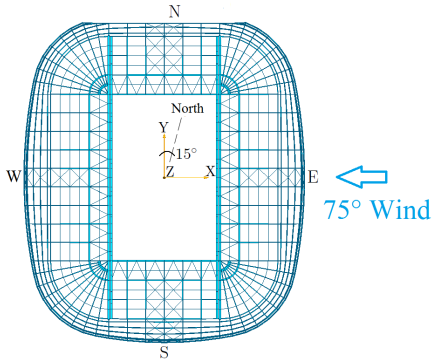


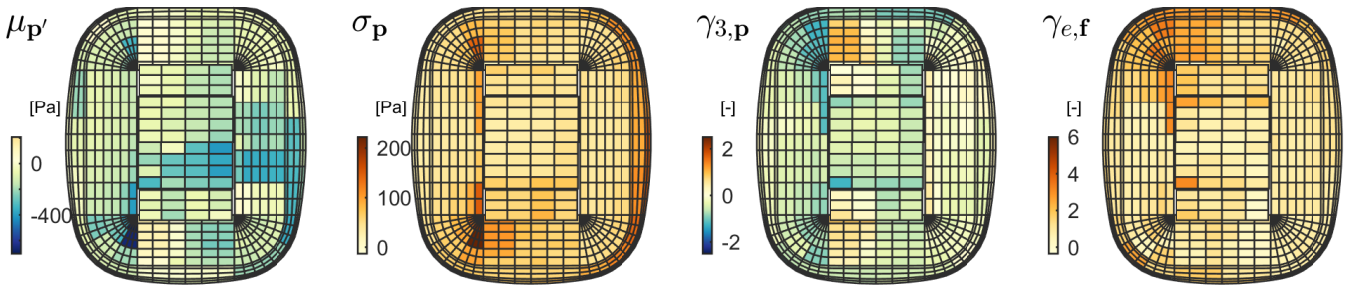
Illustration: Lille's stadium

- Aerodynamic pressure field: Wind tunnel measurements (CSTB, France)

1/200-scaled model (rigid) of the stadium[1]



- Wind direction 75°:

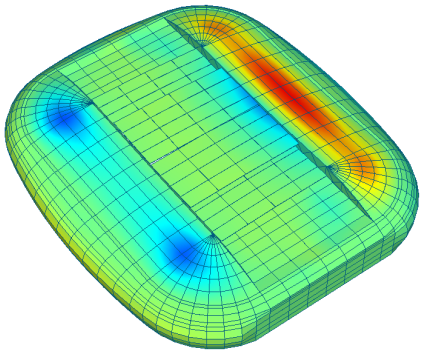


[1] Wind tunnel simulations at the Centre Scientifique et Technique du Bâtiment (CSTB) in Nantes, France

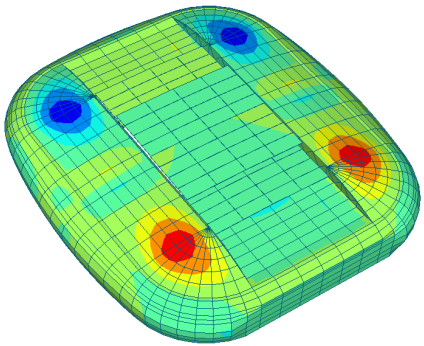
Illustration: Lille's stadium

- Structural dynamic analysis
  - Strong dynamic structural behavior
  - Nodal background/Modal resonant analysis
  - The first 21 modes are kept, unique modal damping 1%
  - Modes 1-11: f_{nat}<1Hz; mode 21: $f_{nat} = 1.41$Hz

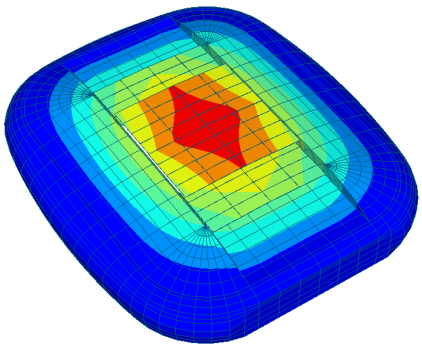
Vertical displacements[1]



mode 1: 0.475 Hz



mode 2: 0.488 Hz



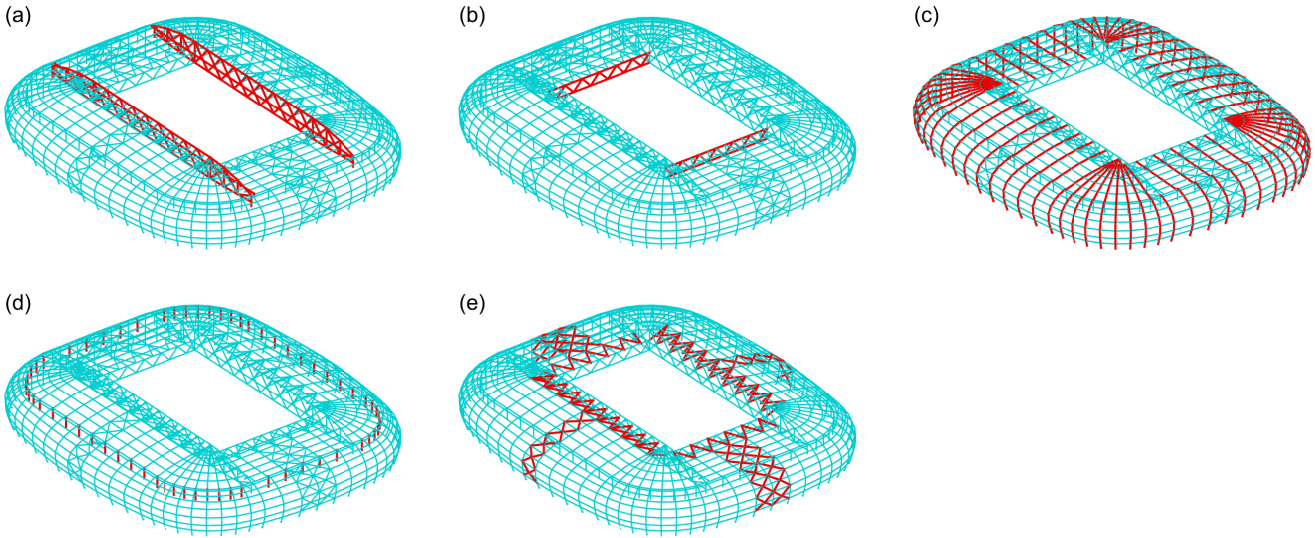
mode 3: 0.517 Hz

- Assumption of Gaussian responses
  - Peak factors: Davenport's model

[1] Computed by the design office Greisch (BEG). http://www.greisch.com/

Illustration: Lille's stadium

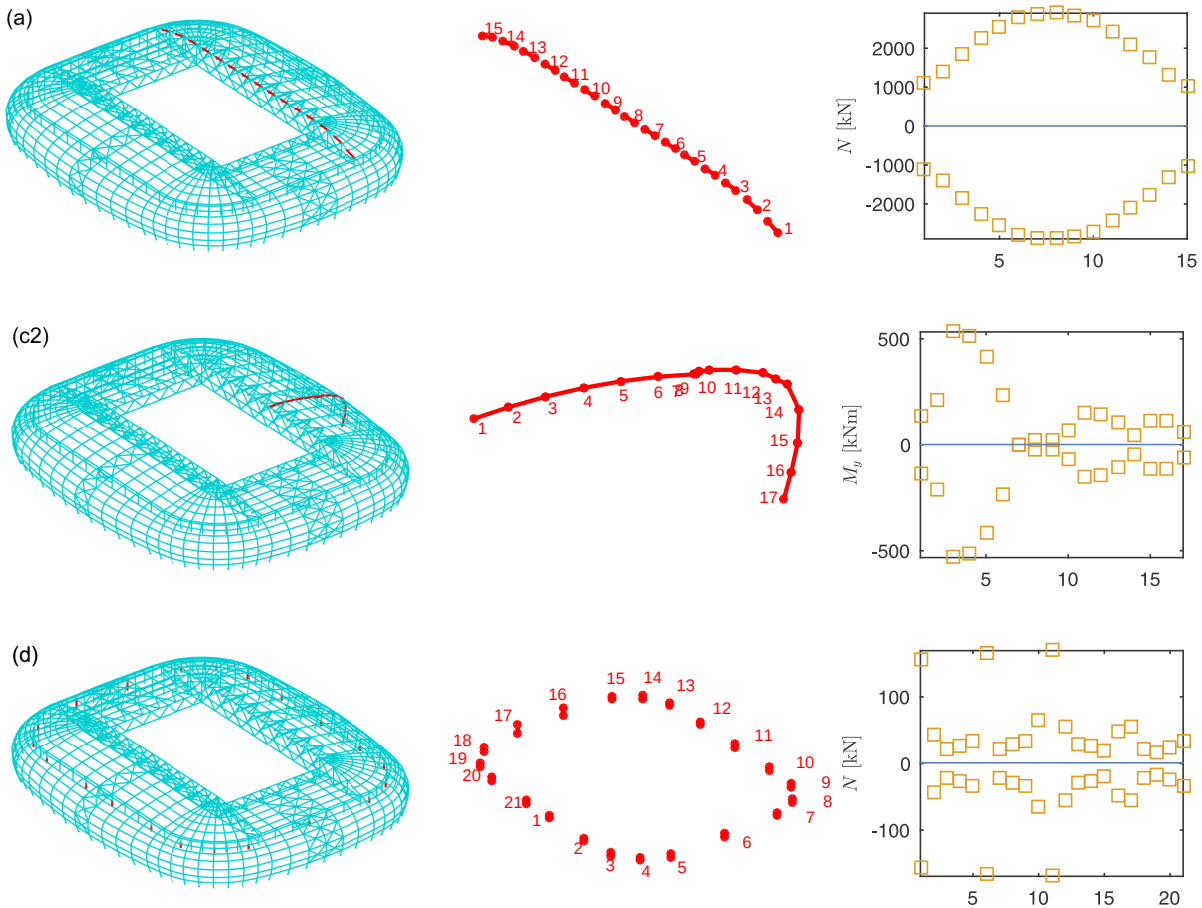
- Envelope: 7994 structural responses are considered



	Type	Elements	Forces	Responses
Large beams$^{(a)}$	Spatial beams	399	N, M_y, M_z, T_y, T_z	1995
Cross-ways beams$^{(b)}$	Spatial beams	65	N, M_y, M_z, T_y, T_z	325
Beams (roof)$^{(c)}$	Spatial beams	1070	N, M_y, M_z, T_y, T_z	5350
Columns$^{(d)}$	Spatial beams	128	N	128
Bracing system$^{(e)}$	Bar	196	N	196
				n_r=7994

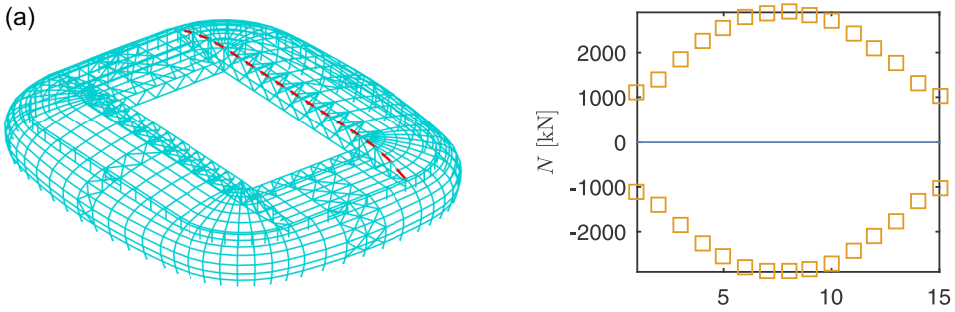
Illustration: Lille's stadium

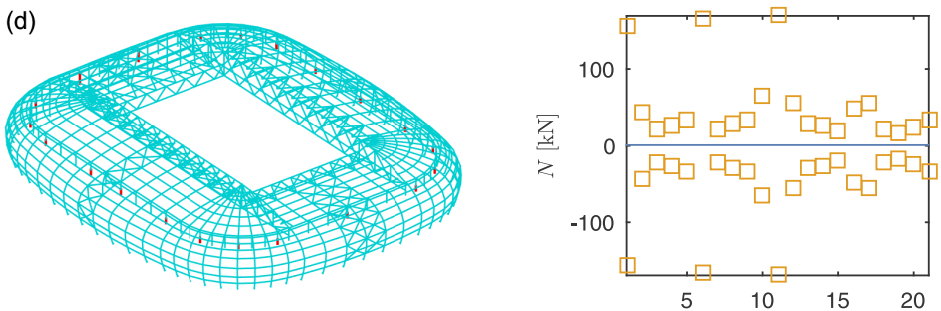
- Example of structural responses



Envelope values

How to establish static wind loads for large civil structures?

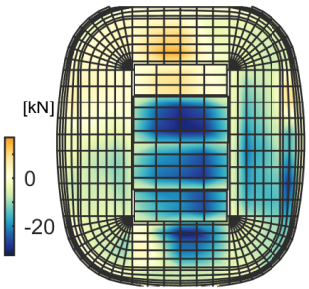




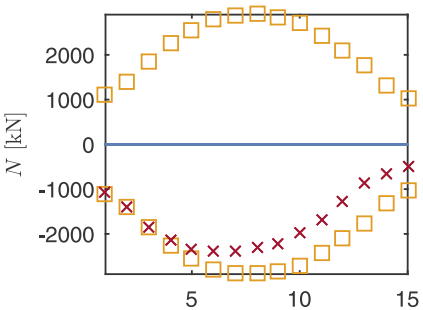
Iterative solution

- Sequential reconstruction of the envelope

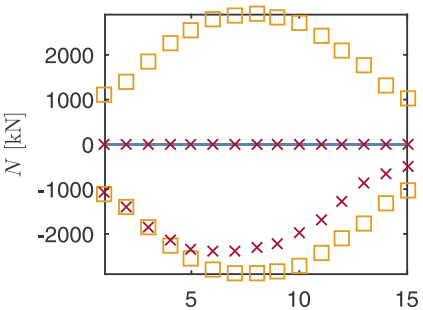
First static load



First static response



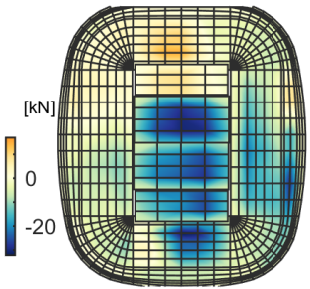
First reconstruction



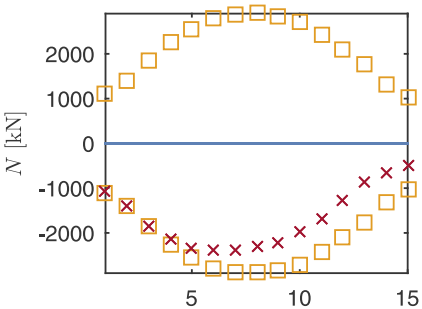
Iterative solution

- Sequential reconstruction of the envelope

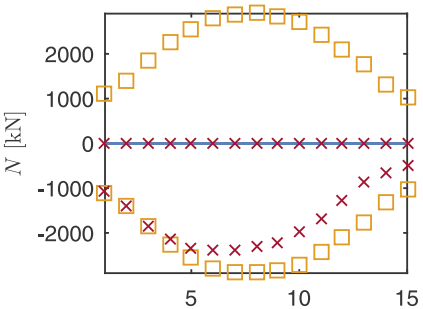
First static load



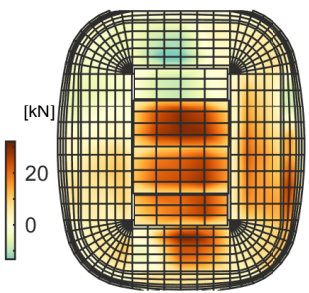
First static response



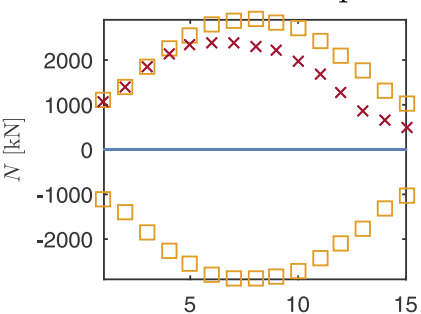
First reconstruction



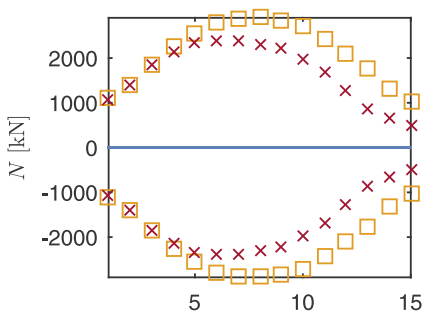
Second static load



Second static response

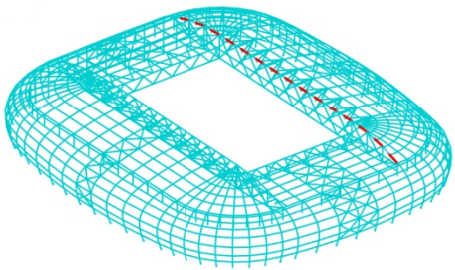


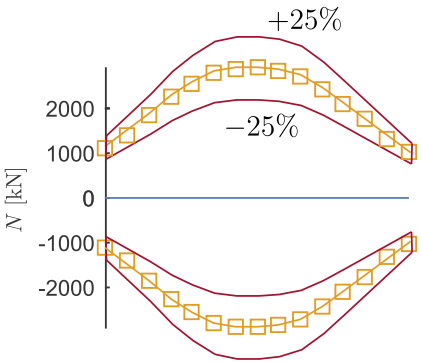
Second reconstruction



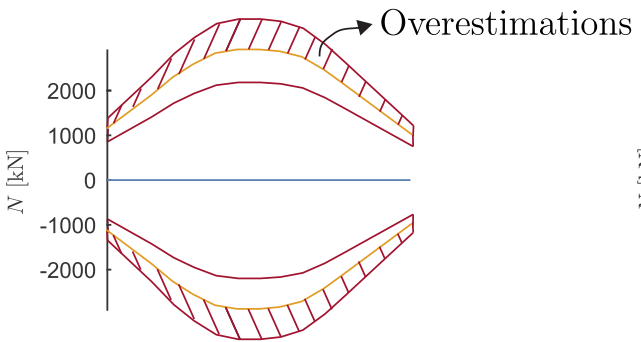
Envelope reconstruction problem

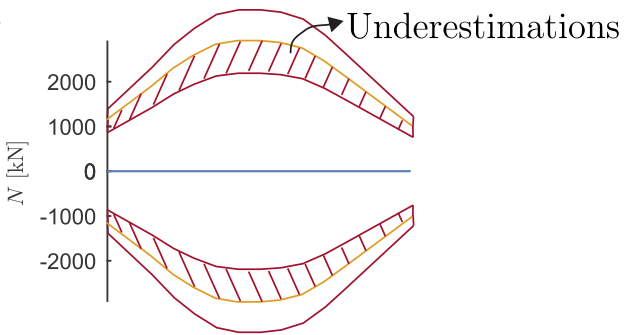
- Tolerance on the reconstruction





- Economic and safe reconstruction





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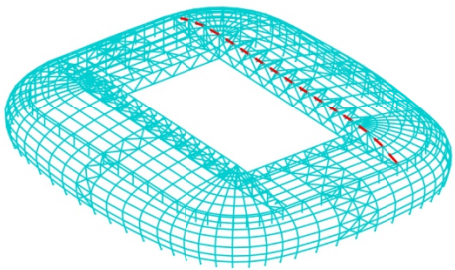

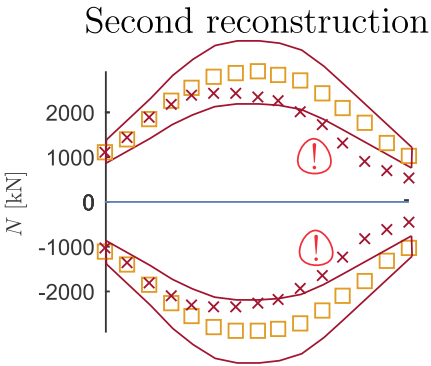

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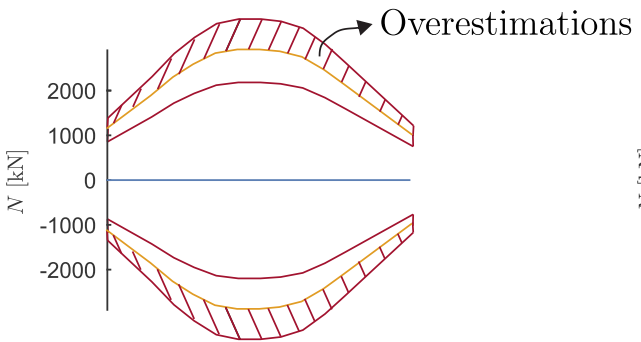
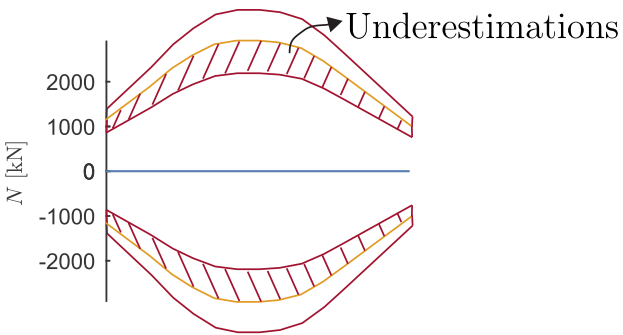
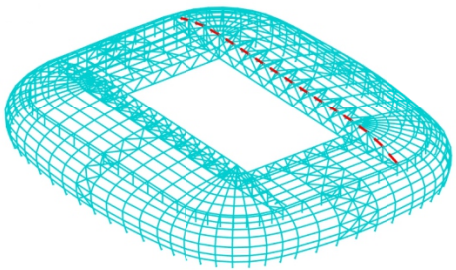
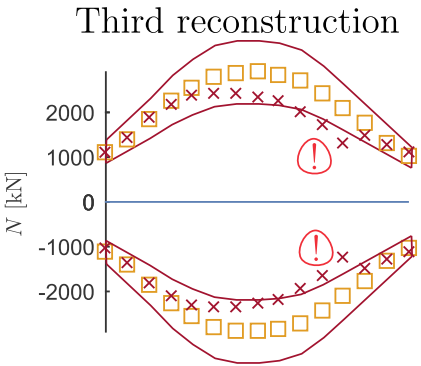




Envelope reconstruction problem

- Tolerance on the reconstruction





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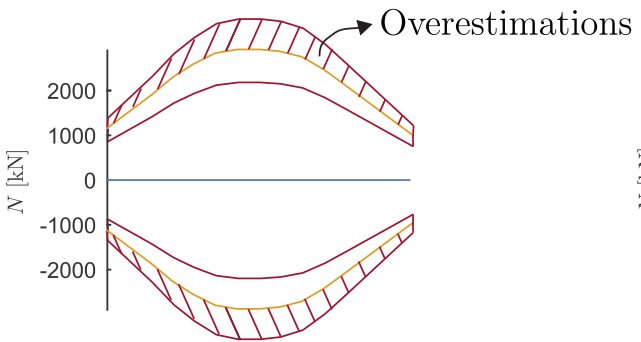

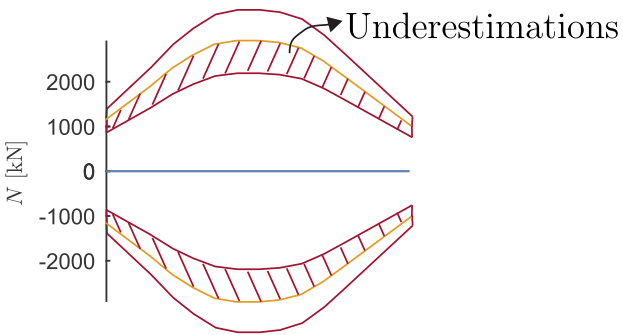

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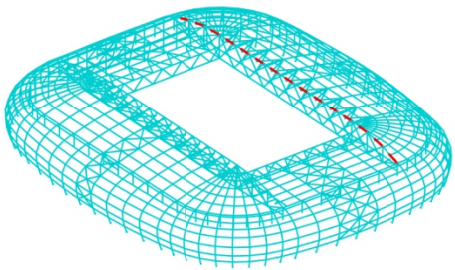

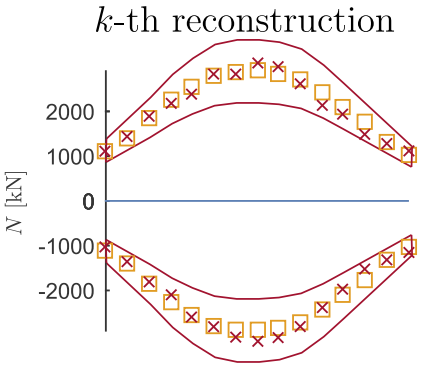

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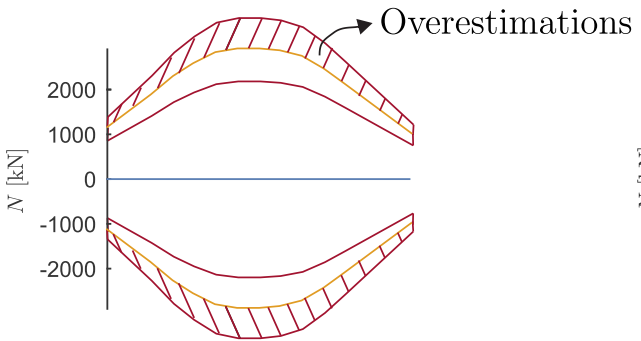

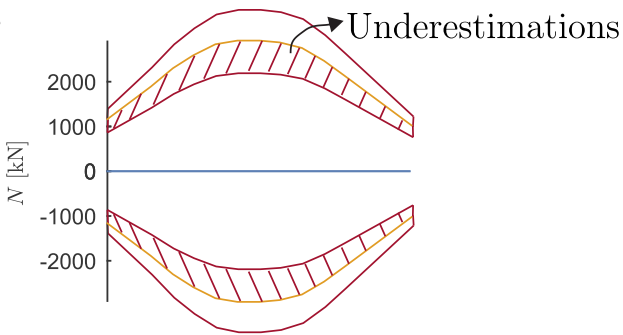

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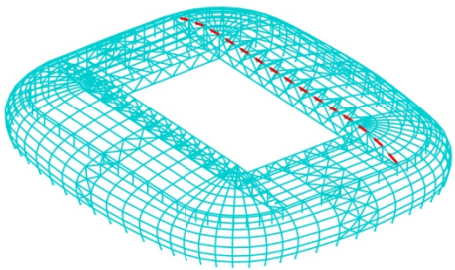

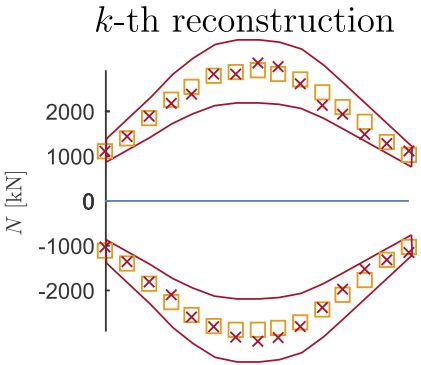

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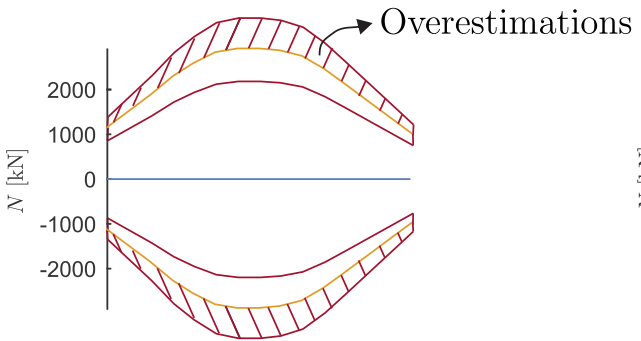
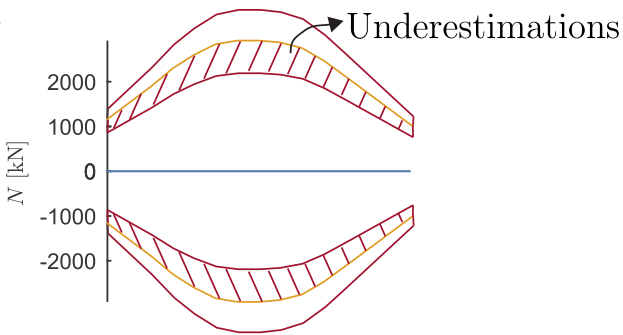




Actual solutions

- Global loading technique (Repetto & Solari, 2004)[1]
  - **Only** relevant for **vertical** structures

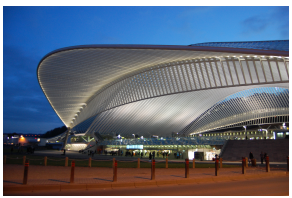
- Universal loads (Katsumura et al., 2007)[2]
  - **Only** relevant for **quasi-static** structural behavior

[1] Repetto M.P., Solari G. (2004). Equivalent static wind actions on vertical structures.
[2] Katsumura A., Tamura Y., Nakamura O. (2007). Universal wind load distribution simultaneously reproducing largest load effects in all subject members on large-span cantilevered roof.

Objective

- Find a methodology
  - Structural behavior: quasi-static or resonant

  - Usual and unusual structures: stadium, tower,...



  - Optimum number of load cases
  - Gaussian and non-Gaussian context
  - Controllable tolerance

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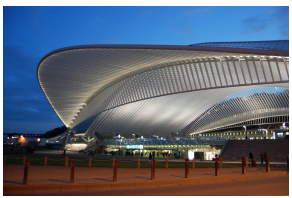
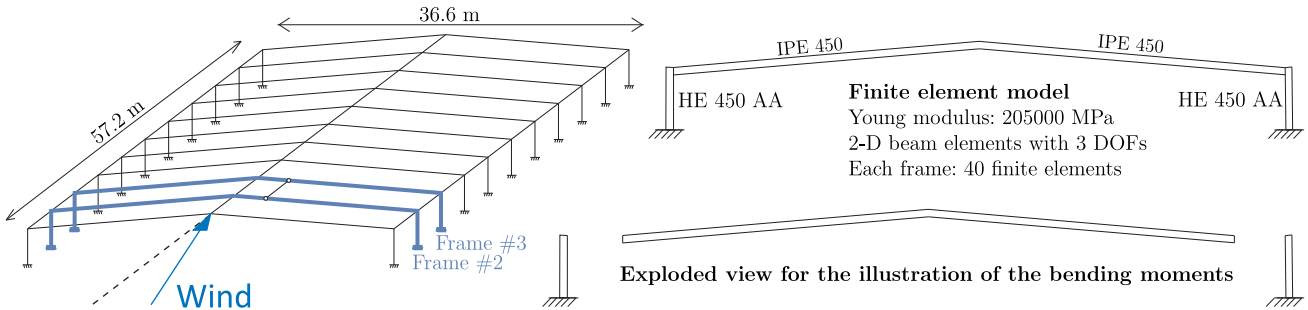


  - Optimum number of load cases
  - Gaussian and non-Gaussian context
  - Controllable tolerance
- Equivalent Static Wind Loads (ESWLs)
- Principal Static Wind Loads (PSWLs)

Structural behavior

Quasi-static structural behaviour

- Illustration: Low-rise rigid gable roof building



- Literature: Conditional Sampling Technique [Holmes (1988)][1]
- Review: Load-Response Correlation method [Kasperski (1992)][2]
- Personal contribution: Conditional $\mathcal{E}$xpected Static Wind Load [Blaise et al (2016)][3]
- Personal contribution: Bicubic model: joint and conditional PDFs [Blaise et al (2016)][3]

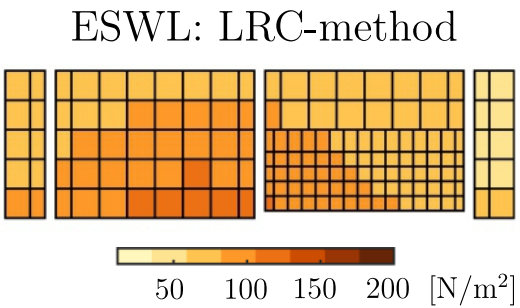
1 Holmes, J. D. (1988). Distribution of peak wind loads on a low-rise building
2 Kasperski, M. (1992). Extreme Wind Load Distributions for Linear and Nonlinear Design.
3 Blaise, N., Canor, T. and Denoël, V. (2016). Reconstruction of the envelope of non-Gaussian structural responses with PSWLs

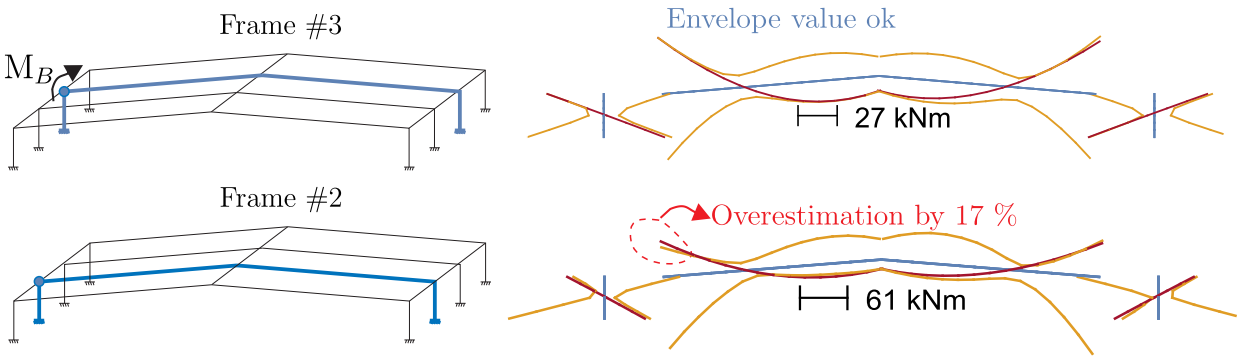
Load-Response Correlation (LRC) method

- Maximum response: $\mathrm{r}_i^{(\max)} = \mathrm{g}^{(\max)} \sigma_{\mathrm{r}_i}$
- Most probable extreme load pattern

$$\mathrm{p}_k^{(\mathcal{L},\max)} = \mathrm{g}^{(\max)} \rho_{\mathrm{p}_k \mathrm{r}_i} \sigma_{\mathrm{p}_k}$$

- PDFs: Gaussian assumption but applicable with non-Gaussian peak factors





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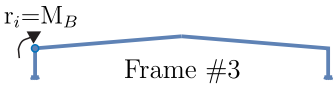
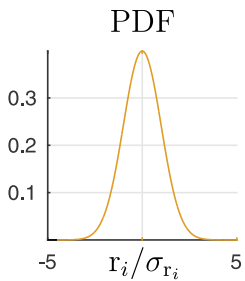
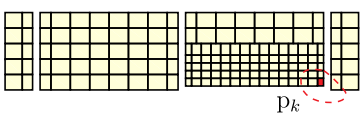
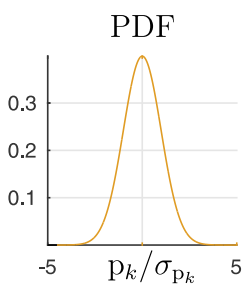
Bending moment $\mathrm{r}_i{=}\mathrm{r}_i^{(\max)}$



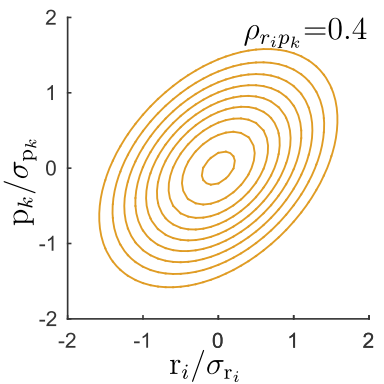


Aerodynamic pressure p_k





Joint response-load PDF



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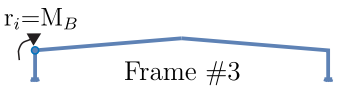
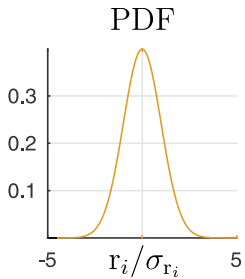
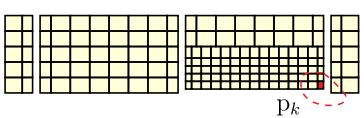
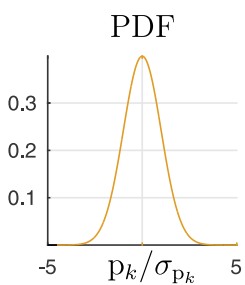


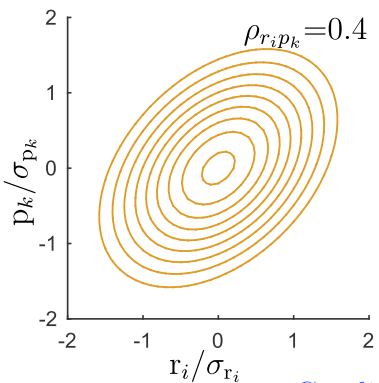


Aerodynamic pressure p_k

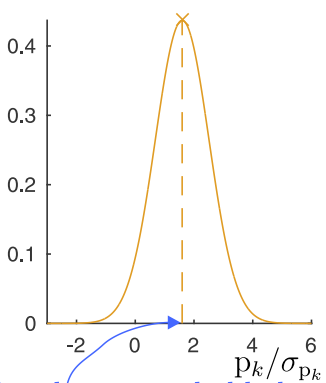




Joint response-load PDF



Conditional load PDF
$\mathrm{r}_i = \mathrm{r}_i^{(\max)}$

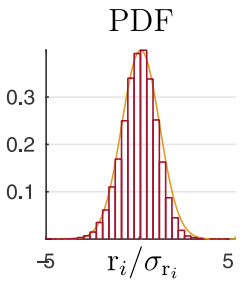


Conditional most probable load
$\mathrm{p}_k^{(\mathcal{L},\max)} = \mathrm{g}^{(\max)} \rho_{\mathrm{p}_k \mathrm{r}_i} \sigma_{\mathrm{p}_k}$

LRC method in a non-Gaussian Framework

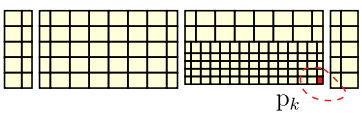
Bending moment $r_i = r_i^{(max)}$

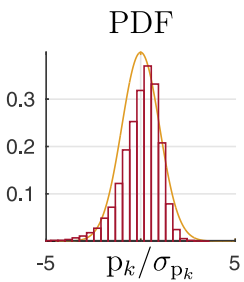
γ_3=-0.16, γ_e=0.36



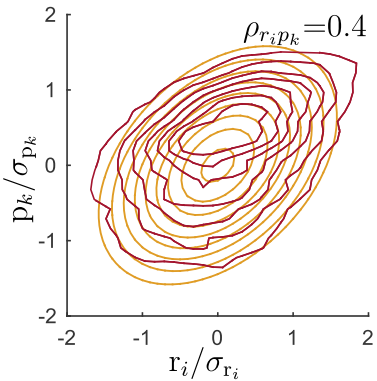
Aerodynamic pressure p_k

γ_3=-1, γ_e=2



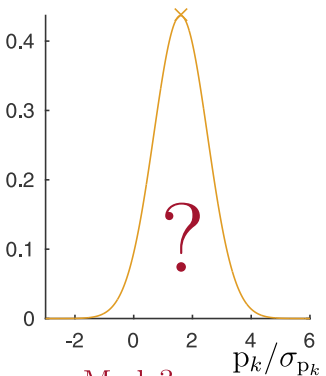


Joint response-load PDF



Conditional load PDF

$r_i = r_i^{(max)}$



Mode?
Median?
Mean?

Conditional $\mathcal{E}$xpected Static Wind Load

Definition

Average of the aerodynamic pressures $\mathbf{p}$ conditioned on producing the i-th envelope response $\mathrm{r}_i^{(\mathrm{m})}$

$$\mathbf{p}^{(\mathcal{E},\mathrm{m})} = \mathbb{E}\left[\mathbf{p}|\mathrm{r}_i = \mathrm{r}_i^{(\mathrm{m})}\right] = \mu_{\mathbf{p}|\mathrm{r}_i}(\mathrm{r}_i^{(\mathrm{m})}),$$

- Conditional PDF of the aerodynamic pressure p_k given the structural response r_i

$$\psi_{\mathrm{p}_k|\mathrm{r}_i}(\mathrm{p}_k, \mathrm{r}_i) = \frac{\psi_{\mathrm{p}_k\mathrm{r}_i}(\mathrm{p}_k, \mathrm{r}_i)}{\psi_{\mathrm{r}_i}(\mathrm{r}_i)}.$$

- Conditional Expected Static Wind Load

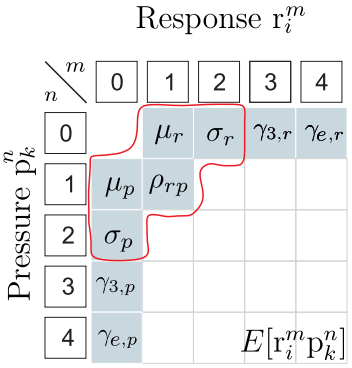
$$\mu_{\mathrm{p}_k|\mathrm{r}_i}(\mathrm{r}_i^{(\mathrm{m})}) = \int_{\mathbb{R}} \mathrm{p}_k\, \psi_{\mathrm{p}_k|\mathrm{r}_i}\left(\mathrm{p}_k, \mathrm{r}_i^{(\mathrm{m})}\right) \mathrm{d}\mathrm{p}_k,$$

Bicubic Model

- 7-parameter model: cubic transformations of both variables (Hermite moment model)

$$\mathrm{p} = g(u) = \frac{\alpha_u}{b_u}\left(\frac{u^3}{3} + a_u u^2 + (b_u - 1)u - a_u\right) \qquad \mathrm{r} = h(v) = \frac{\alpha_v}{b_v}\left(\frac{v^3}{3} + a_v v^2 + (b_v - 1)v - a_v\right)$$

α_u, b_u, a_u: Match σ_p, $\gamma_{3,\mathrm{p}}$ and $\gamma_{e,\mathrm{p}}$
α_v, b_v, a_v: Match σ_r, $\gamma_{3,\mathrm{r}}$ and $\gamma_{e,\mathrm{r}}$
ρ_{uv}: Match correlation coefficient ρ_{rp}



Gaussian assumption

- Joint and conditional PDFs

$$\psi^{\mathcal{B}}_{\mathrm{pr}}(\mathrm{p},\mathrm{r}) = \frac{\psi^{\mathcal{N}}_{uv}(u(\mathrm{p}), v(\mathrm{r}))}{|J(u(\mathrm{p}), v(\mathrm{r}))|}, \qquad \psi^{\mathcal{B}}_{\mathrm{p}|\mathrm{r}}(\mathrm{p},\mathrm{r}) = \frac{\psi^{\mathcal{N}}_{u|v}(u(\mathrm{p}), v(\mathrm{r}))}{\left|\frac{\mathrm{d}g}{\mathrm{d}u}(u(\mathrm{p}))\right|}$$

- Conditional expected value

$$\mu^{\mathcal{B}}_{\mathrm{p}|\mathrm{r}}(\mathrm{r}) = \frac{\alpha_u}{3b_u}\left(\left(v(\mathrm{r})^3 - 3v(\mathrm{r})\right)\rho^3_{uv} + 3a_u\left(v(\mathrm{r})^2 - 1\right)\rho^2_{uv} + 3b_u v(\mathrm{r})\rho_{uv}\right)$$

  - Gaussian framework: $\mu^{\mathcal{B}}_{\mathrm{p}|\mathrm{r}^{(\max)}}(\mathrm{r}) = \mathrm{g}^{(\max)}\rho_{\mathrm{p}_k\mathrm{r}_i}\sigma_{\mathrm{p}_k}$

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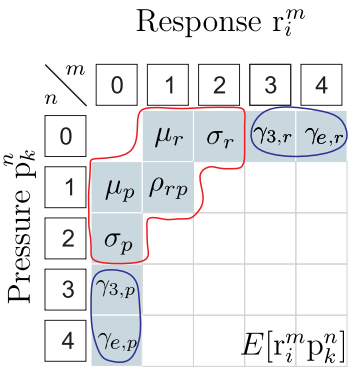

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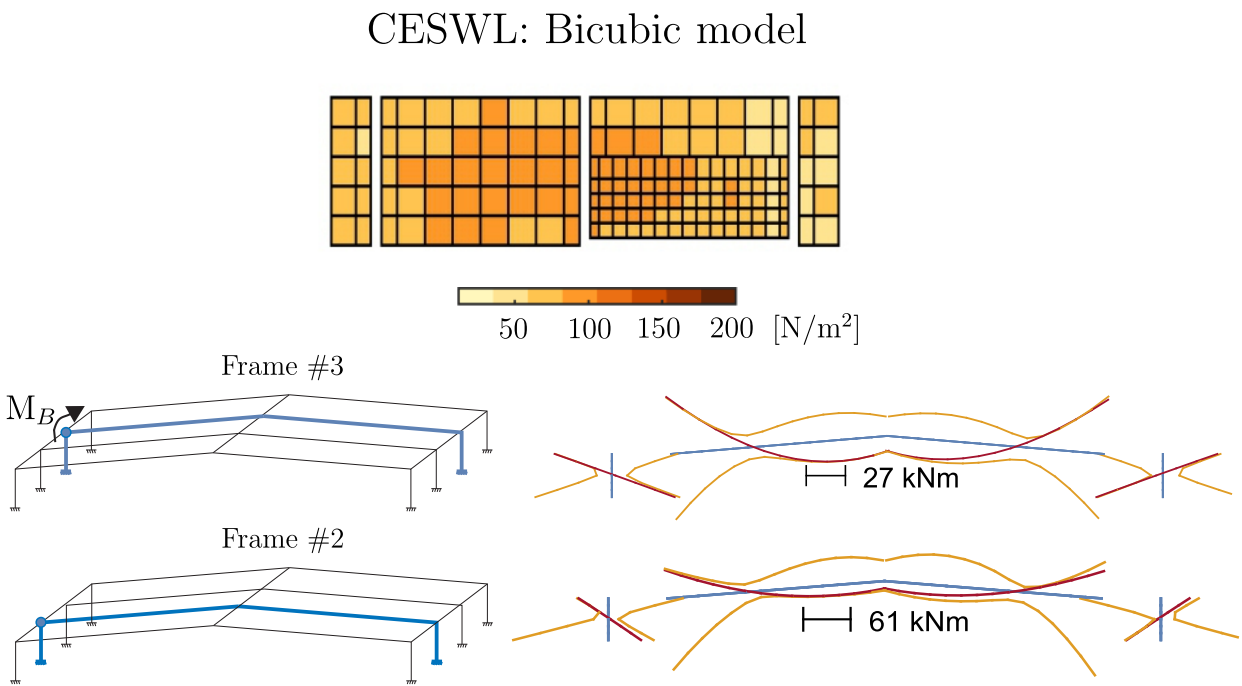
  - Gaussian framework: $\mu^{\mathcal{B}}_{\mathrm{p}|\mathrm{r}^{(\max)}}(\mathrm{r}) = \mathrm{g}^{(\max)}\rho_{\mathrm{p}_k \mathrm{r}_i}\sigma_{\mathrm{p}_k}$

Bicubic Model

- Conditional Expected Static Wind Load (Bicubic model)
  - ☐ Envelope value: ✓
  - ☐ No overestimation in the entire envelope



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Bending moment $r_i = r_i^{(max)}$

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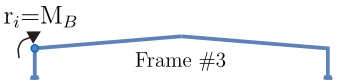
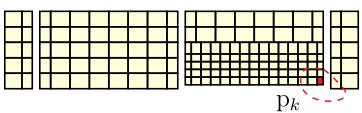
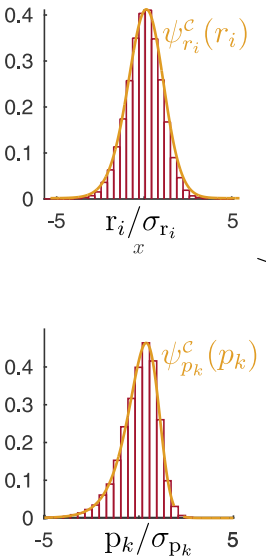


Aerodynamic pressure p_k

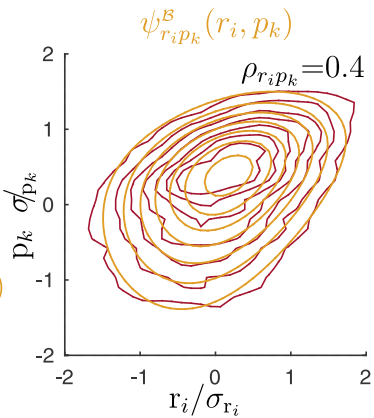
γ_3=-1, γ_e=2



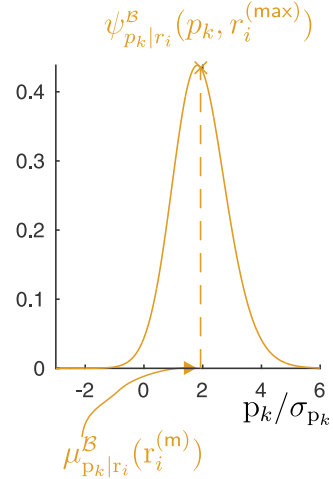
PDF



joint PDF

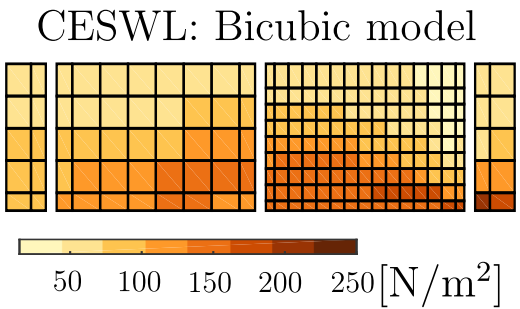


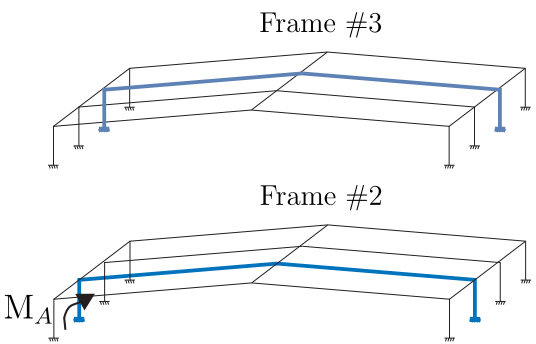
Conditional PDF

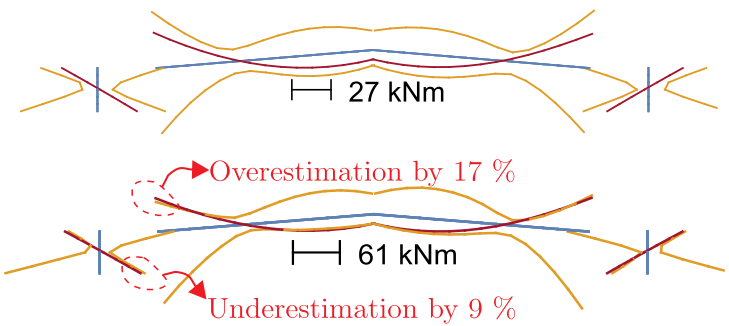


Bicubic Model

- Conditional Expected Static Wind Load (Bicubic model)
  - Envelope value: Underestimation by 9% (LRC method ✓)
  - Overestimation by 17% (LRC method 40%)







Bicubic Model

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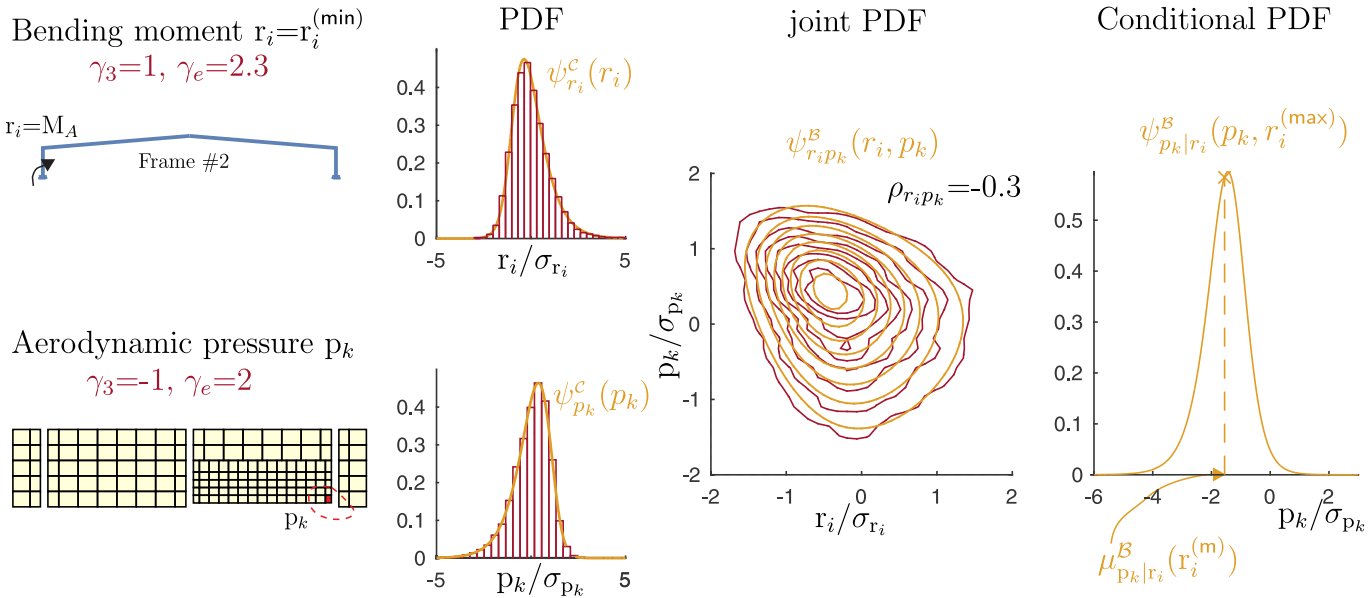
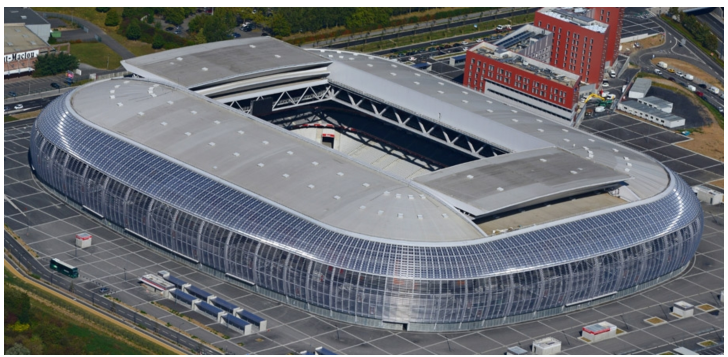


Structural behavior

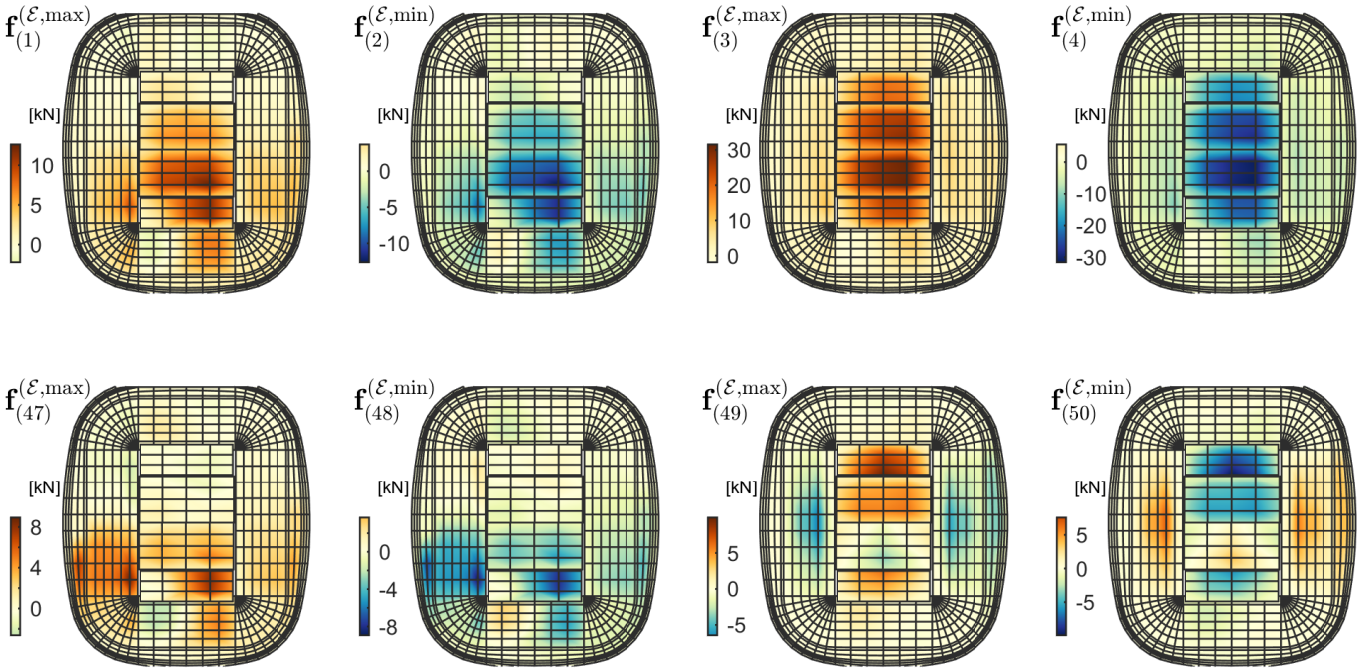
- **Dynamic structural behaviour**
  - Illustration: Lille's stadium



- Review: Hybrid-based ESWLs (extend the LRC method) (Chen et al., 2001)
- Personnal contribution: Formulation of the Conditional $\mathcal{E}$xpected Static Wind Load with elastic forces

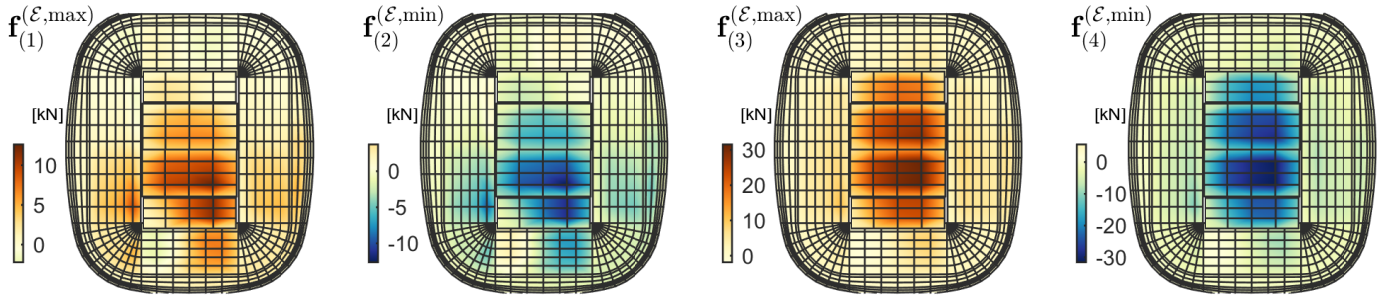
Gaussian framework

- Envelope: 15988 envelope values are considered
- 15988 Conditional Expected Static Wind Loads

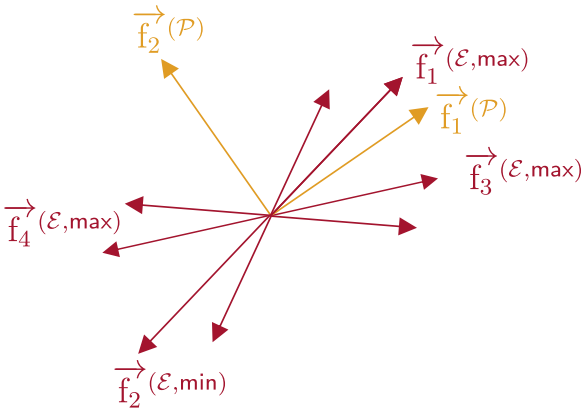


Optimum basis

- 15988 CESWLs

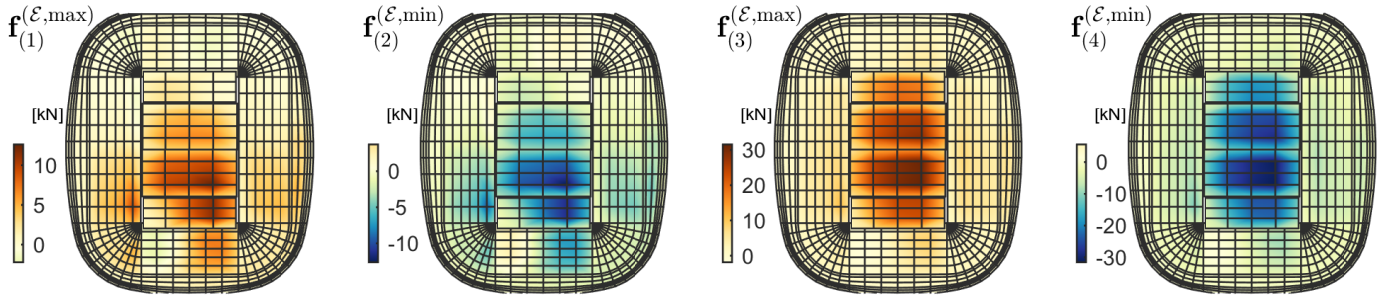


- CESWLs basis: Principal directions?



Conditional expected static wind load matrix

- CESWLs



- Matrix $\mathbf{F}^{(\mathcal{E})}$

$$\begin{pmatrix} F_{11}^{(\mathcal{E},\min)} & F_{12}^{(\mathcal{E},\max)} & F_{13}^{(\mathcal{E},\min)} & \cdots\cdots & F_{1N}^{(\mathcal{E},\max)} \\ \vdots & \vdots & \vdots & \cdots\cdots & \vdots \\ \vdots & \vdots & \vdots & \cdots\cdots & \vdots \\ F_{I1}^{(\mathcal{E},\min)} & F_{I2}^{(\mathcal{E},\max)} & F_{I4}^{(\mathcal{E},\min)} & \cdots\cdots & F_{IN}^{(\mathcal{E},\max)} \end{pmatrix}_{I\times N}$$

- I = Number of DOFs (Lille's stadium= **15288**)
- N =Number of envelope values (Lille's stadium= **15988**)

Principal Static Wind Loads

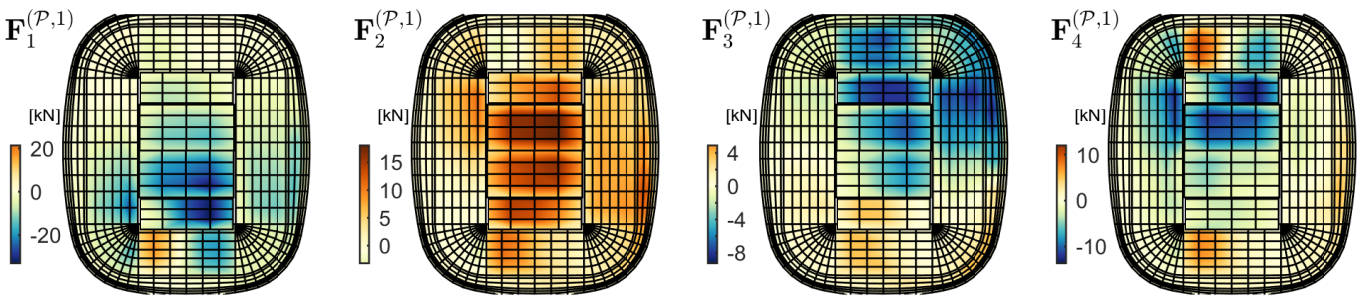
■ Singular value decomposition of the CESWL matrix $\mathbf{F}^{(\mathcal{E})}$

$$\underset{}{\mathbf{F}^{(\mathcal{E})}} \quad \underset{}{\mathbf{F}^{(\mathcal{P})}} \quad \underset{}{\mathbf{s}} \quad \underset{}{\mathbf{v}'}$$

$$\begin{pmatrix} F_{11}^{(\mathcal{E},\min)} & \cdots & F_{1N}^{(\mathcal{E},\max)} \\ \vdots & \ddots & \\ F_{l1}^{(\mathcal{E},\min)} & & F_{lN}^{(\mathcal{E},\max)} \end{pmatrix} = \begin{pmatrix} F_{11}^{(\mathcal{P})} & \cdots & F_{1M}^{(\mathcal{P})} \\ \vdots & \ddots & \\ F_{l1}^{(\mathcal{P})} & & F_{mM}^{(\mathcal{P})} \end{pmatrix} \begin{pmatrix} s_{11} & & 0 \\ & \ddots & \\ 0 & & s_{MM} \end{pmatrix} \begin{pmatrix} v_{11} & \cdots & v_{1N} \\ \vdots & \ddots & \\ v_{M1} & & v_{MN} \end{pmatrix}$$

$$15288 \times 15988 \qquad 15288 \times M \qquad M \times M \qquad M \times 15988$$

where $\mathbf{F}^p$ collects the **Principal Static Wind Load** (PSWL) basis[1].



1 Blaise, N. and V. Denoël (2013). "Principal Static Wind Loads." Journal of Wind Engineering and Industrial Aerodynamics

Principal Static Wind Loads

- Singular value decomposition of the CESWL matrix $\mathbf{F}^{(\mathcal{E})}$

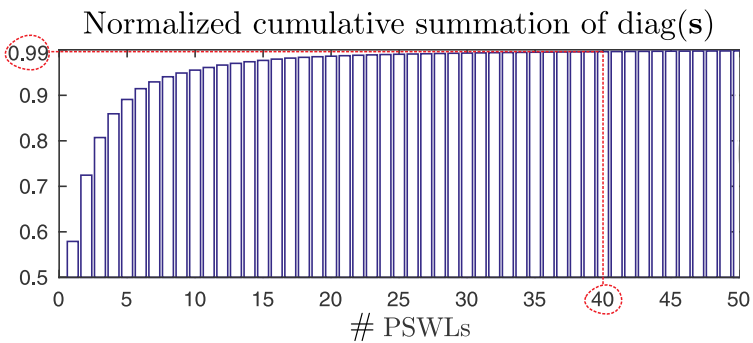
$$\underset{}{\mathbf{F}^{(\mathcal{E})}} \quad \underset{}{\mathbf{F}^{(\mathcal{P})}} \quad \underset{}{\mathbf{s}} \quad \underset{}{\mathbf{v}'}$$

$$\begin{pmatrix} F_{11}^{(\mathcal{E},\min)} & \cdots & F_{1N}^{(\mathcal{E},\max)} \\ \vdots & \ddots & \\ F_{l1}^{(\mathcal{E},\min)} & & F_{lN}^{(\mathcal{E},\max)} \end{pmatrix} = \begin{pmatrix} F_{11}^{(\mathcal{P})} & \cdots & F_{1M}^{(\mathcal{P})} \\ \vdots & \ddots & \\ F_{l1}^{(\mathcal{P})} & & F_{mM}^{(\mathcal{P})} \end{pmatrix} \begin{pmatrix} s_{11} & & 0 \\ & \ddots & \\ 0 & & s_{MM} \end{pmatrix} \begin{pmatrix} v_{11} & \cdots & v_{1N} \\ \vdots & \ddots & \\ v_{M1} & & v_{MN} \end{pmatrix}$$

$$15288 \times 15988 \qquad 15288 \times M \qquad M \times M \qquad M \times 15988$$

where $\mathbf{F}^p$ collects the **Principal Static Wind Load** (PSWL) basis[1].

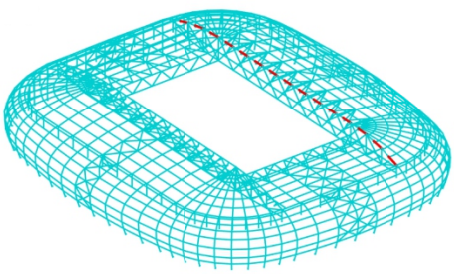
- Convergence of the decomposition $\rightarrow$ $\mathbf{M = 40 \lll 15288}$

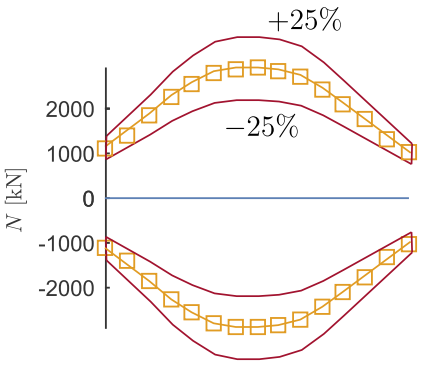


1 Blaise, N. and V. Denoël (2013). "Principal Static Wind Loads." Journal of Wind Engineering and Industrial Aerodynamics

Envelope reconstruction problem

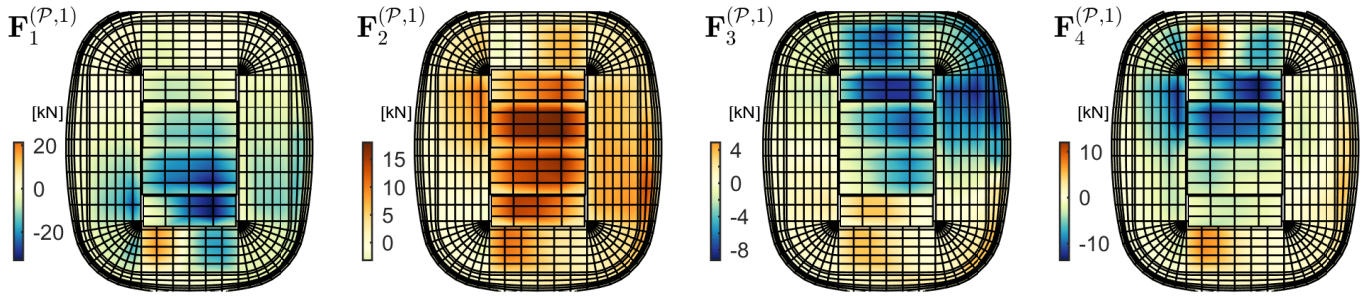
Option 1. Straightforward approach: successively apply PSWLs



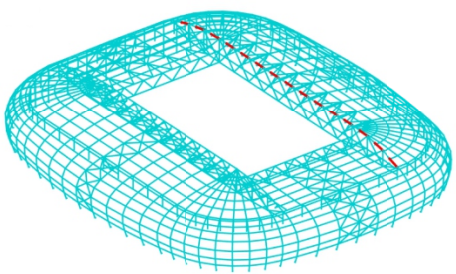


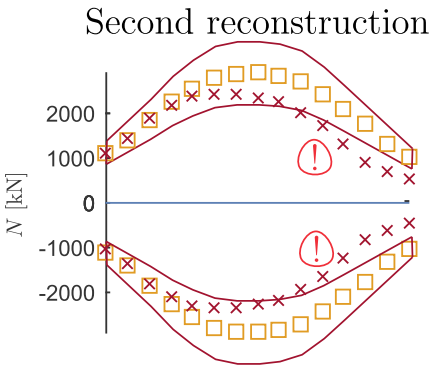
Envelope reconstruction problem

- Straightforward approach: successively apply PSWLs



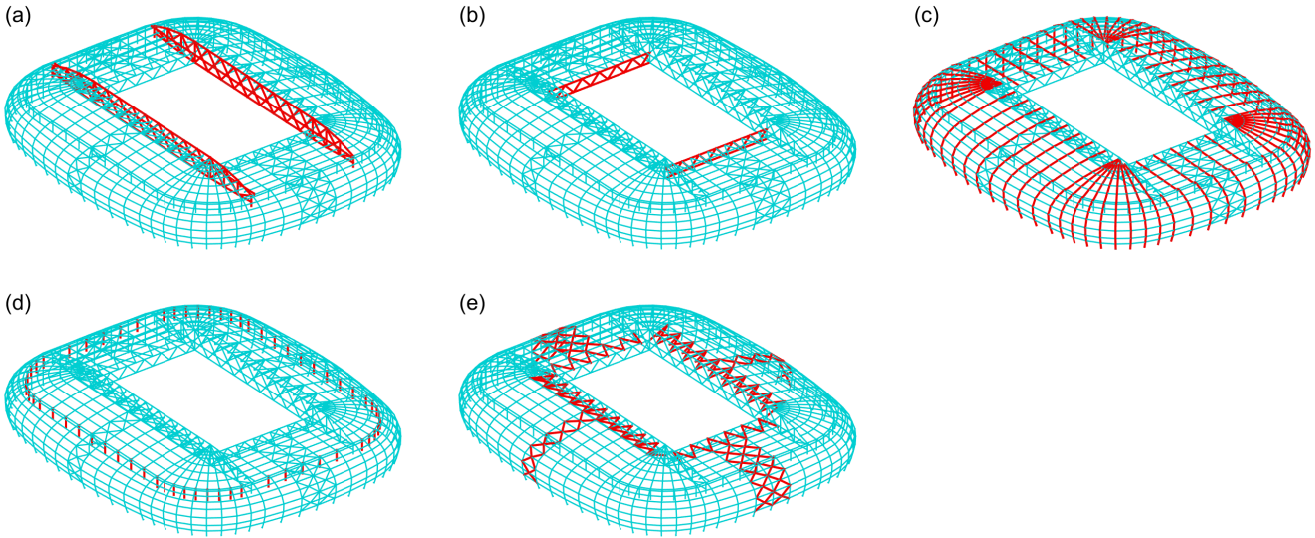
- Number of responses (out of 15988) outside the tolerance [-25%,25%]





Envelope reconstruction problem

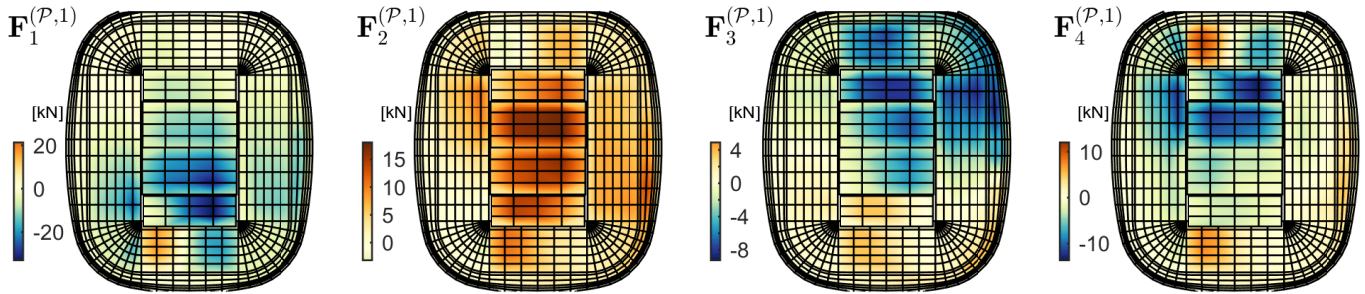
- Envelope: 7994 structural responses are considered



	Type	Elements	Forces	Responses
Large beams$^{(a)}$	Spatial beams	399	N, M_y, M_z, T_y, T_z	1995
Cross-ways beams$^{(b)}$	Spatial beams	65	N, M_y, M_z, T_y, T_z	325
Beams (roof)$^{(c)}$	Spatial beams	1070	N, M_y, M_z, T_y, T_z	5350
Columns$^{(d)}$	Spatial beams	128	N	128
Bracing system$^{(e)}$	Bar	196	N	196
				n_r=7994

Envelope reconstruction problem

- Straightforward approach: successively apply PSWLs



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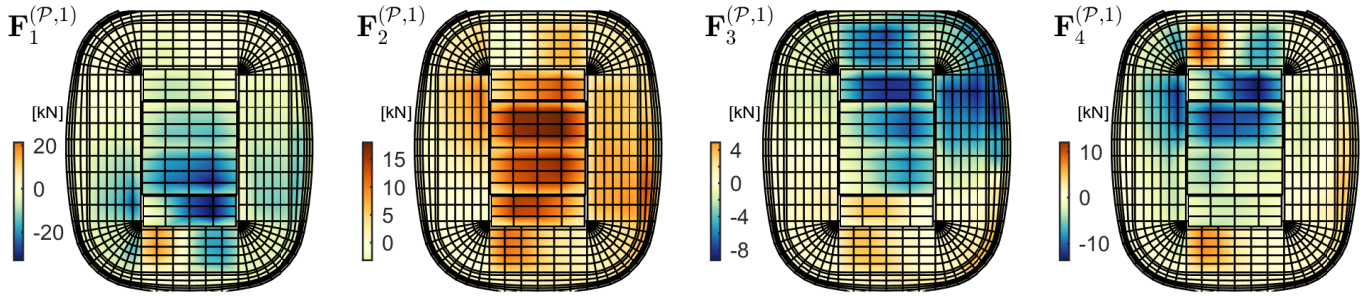
Envelope reconstruction problem

- Straightforward approach: successively apply PSWLs



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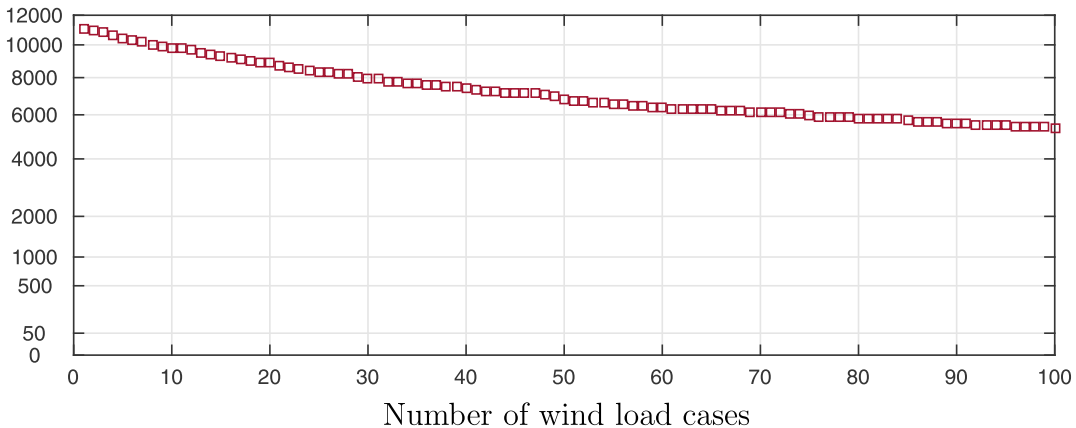
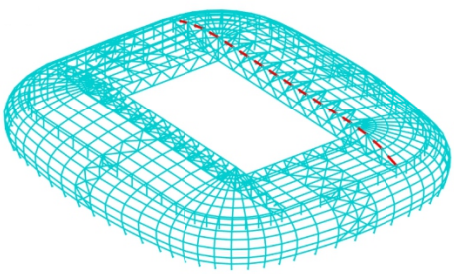
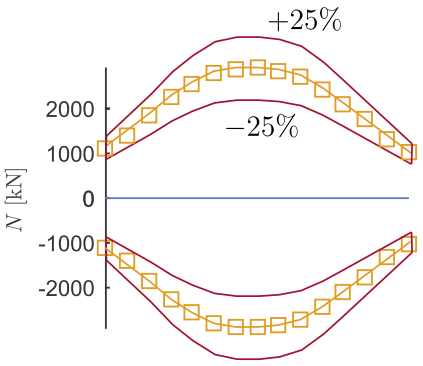


Combinations of PSWLs

Option 2. Combinations of PSWLs





Combinations of PSWLs

- Select n_q PSWLs

$$\{\mathbf{F}_1^{(\mathcal{P})}, \mathbf{F}_2^{(\mathcal{P})}, \ldots, \mathbf{F}_{n_q}^{(\mathcal{P})}\},$$

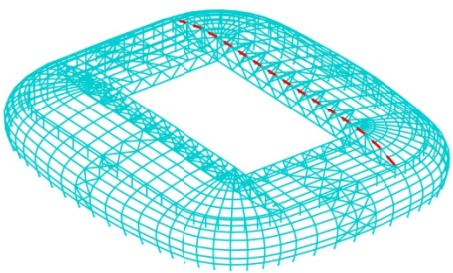
- Combinations of the first n_q PSWLs

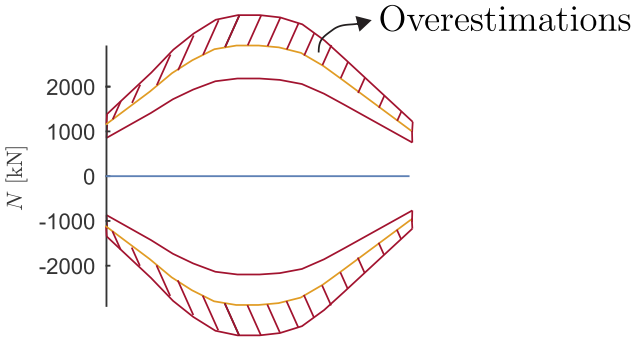
$$\mathbf{f}_{(k)}^{(s)} = [\mathbf{F}_1^{(\mathcal{P})}, \mathbf{F}_2^{(\mathcal{P})}, \ldots, \mathbf{F}_{n_q}^{(\mathcal{P})}]\mathbf{q}_{(k)}^{(\mathcal{P})},$$

- Combinations coefficients: Constrained nonlinear optimization algorithm

$$\min_{\mathbf{q}_{(k)}^{(\mathcal{P})}} \left| \frac{1}{n_r} \sum_{i=1}^{n_r} \varepsilon_{i,(k)}^{(\min)} + \frac{1}{n_r} \sum_{i=1}^{n_r} \varepsilon_{i,(k)}^{(\max)} \right|,$$

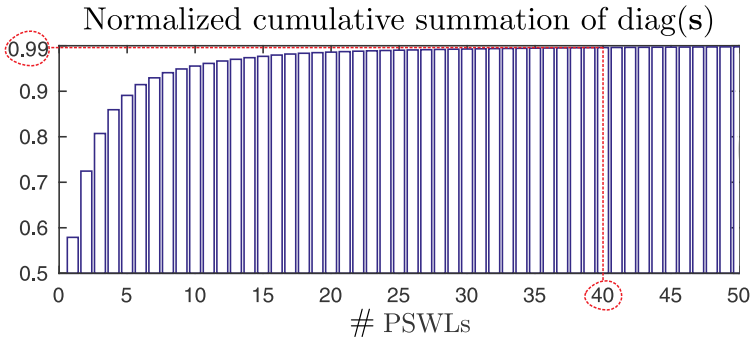
- Linear constraints: acceptable overestimation condition



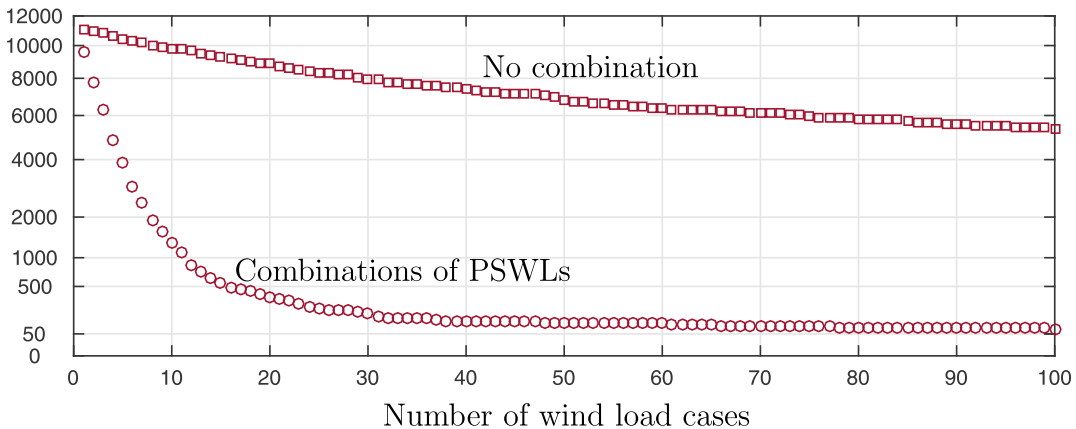


Envelope reconstruction problem

- Combinations of the first 40 PSWLs



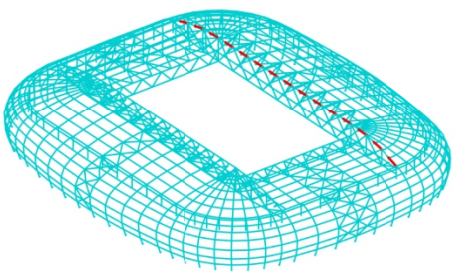
- Number of responses (out of 15988) outside the tolerance [-25%,25%]

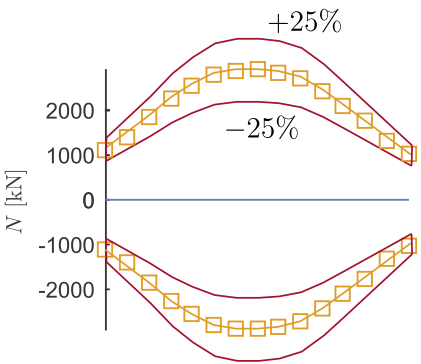


Envelope reconstruction problem

Option 3. Combinations of PSWLs

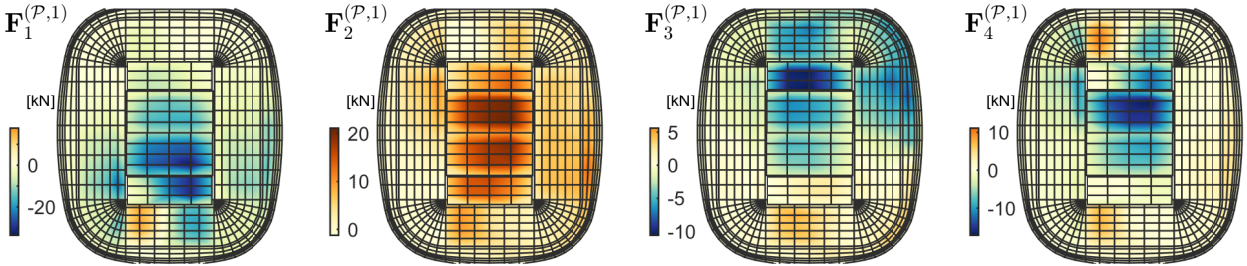
Updating the PSWL basis





Envelope reconstruction problem

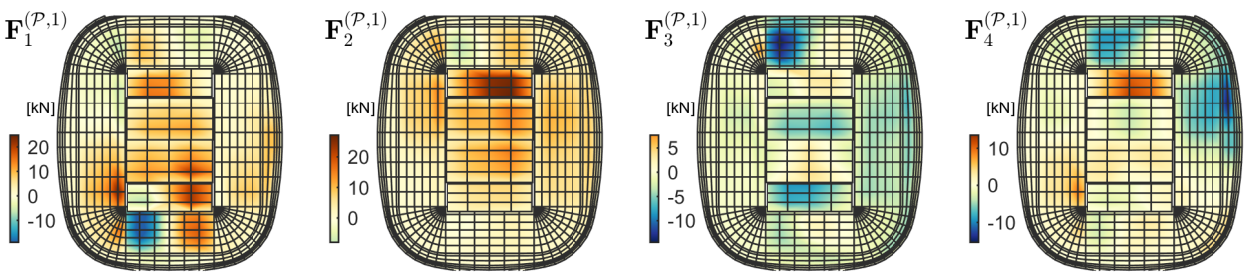
Primary PSWL basis



Updating the PSWL basis after 50 load cases with the 114 CESWLs

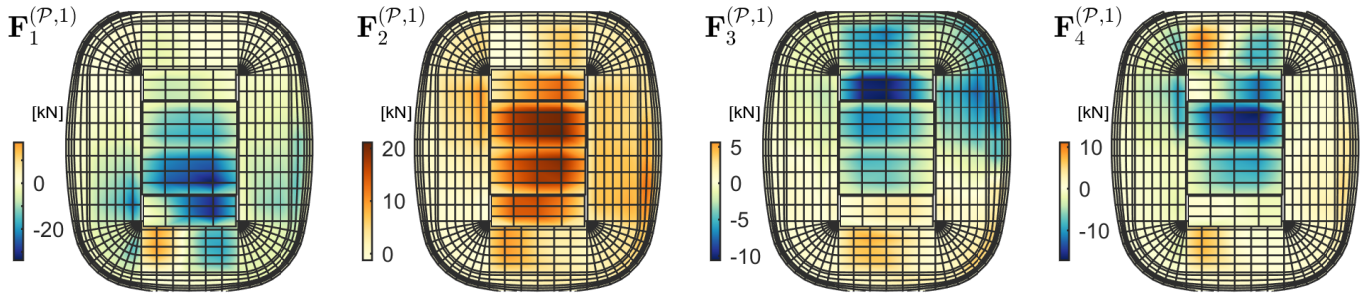
$$\underset{15288\times 114}{\mathbf{F}^{(\mathcal{E})}} = \underset{15288\times M}{\mathbf{F}^{(\mathcal{P})}} \; \underset{M\times M}{\mathbf{s}} \; \underset{M\times 114}{\mathbf{v}'}$$

$$\begin{pmatrix} F_{11}^{(\mathcal{E},\min)} & \cdots & F_{1N}^{(\mathcal{E},\max)} \\ \vdots & \ddots & \\ F_{I1}^{(\mathcal{E},\min)} & & F_{IN}^{(\mathcal{E},\max)} \end{pmatrix} = \begin{pmatrix} F_{11}^{(\mathcal{P})} & \cdots & F_{1M}^{(\mathcal{P})} \\ \vdots & \ddots & \\ F_{I1}^{(\mathcal{P})} & & F_{mM}^{(\mathcal{P})} \end{pmatrix} \begin{pmatrix} s_{11} & & 0 \\ & \ddots & \\ 0 & & s_{MM} \end{pmatrix} \begin{pmatrix} v_{11} & \cdots & v_{1N} \\ \vdots & \ddots & \\ v_{M1} & & v_{MN} \end{pmatrix}$$

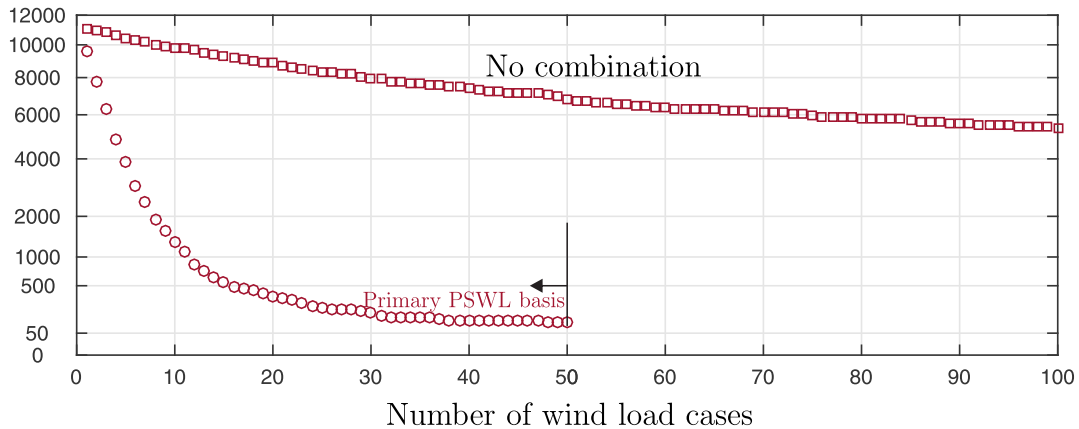


Envelope reconstruction problem

Primary PSWL basis

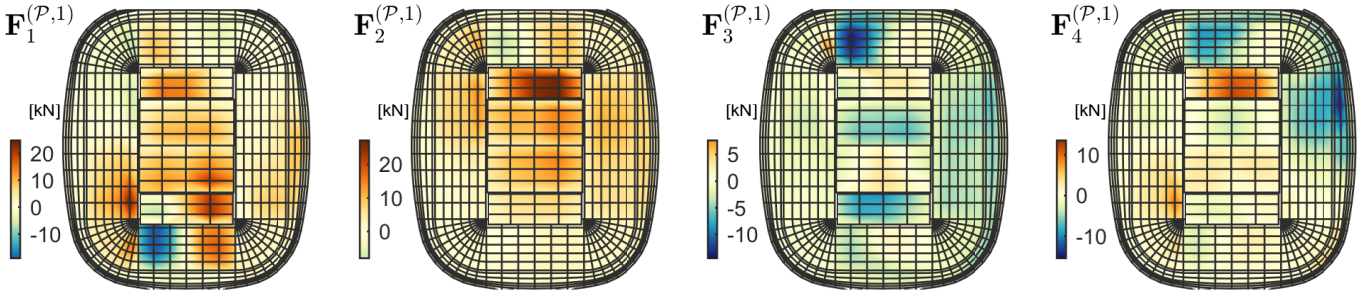


Number of responses (out of 15988) outside the tolerance [-25%,25%]

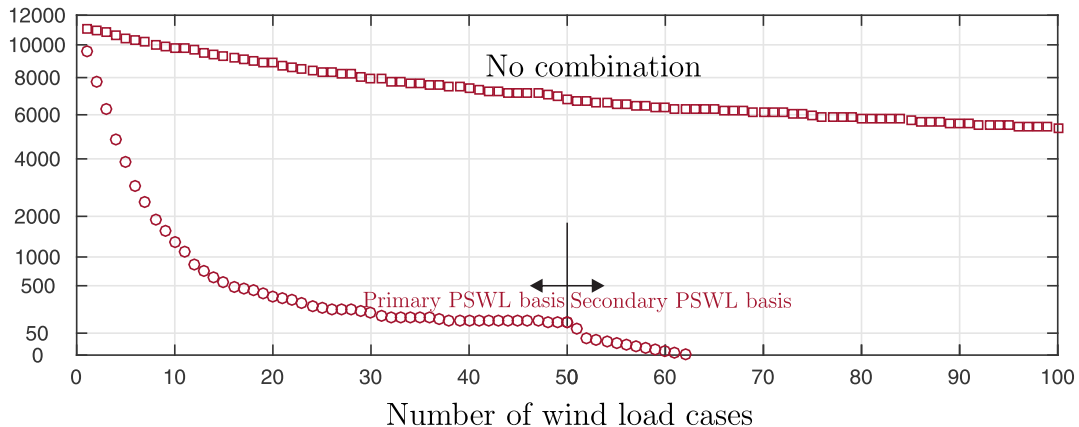


Envelope reconstruction problem

Secondary PSWL basis



- Number of responses (out of 15988) outside the tolerance [-25%,25%]

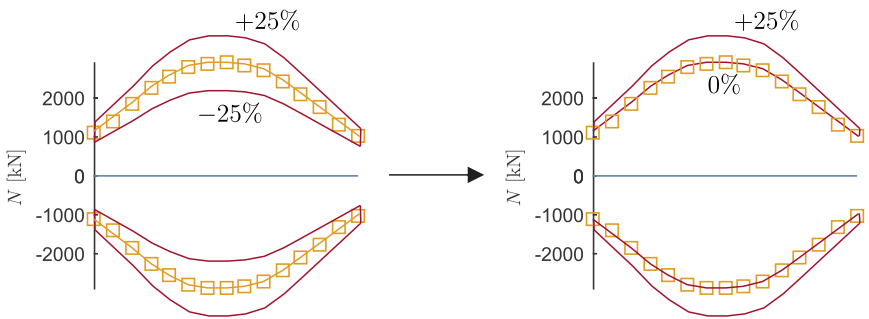


Envelope reconstruction problem

Option 3. Combinations of PSWLs

Updating the PSWL basis (Automatic procedure)

Non-Gaussian framework

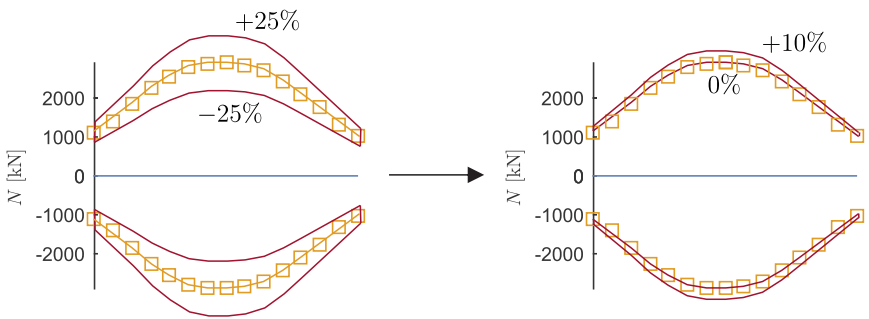


Envelope reconstruction problem

Option 3. Combinations of PSWLs

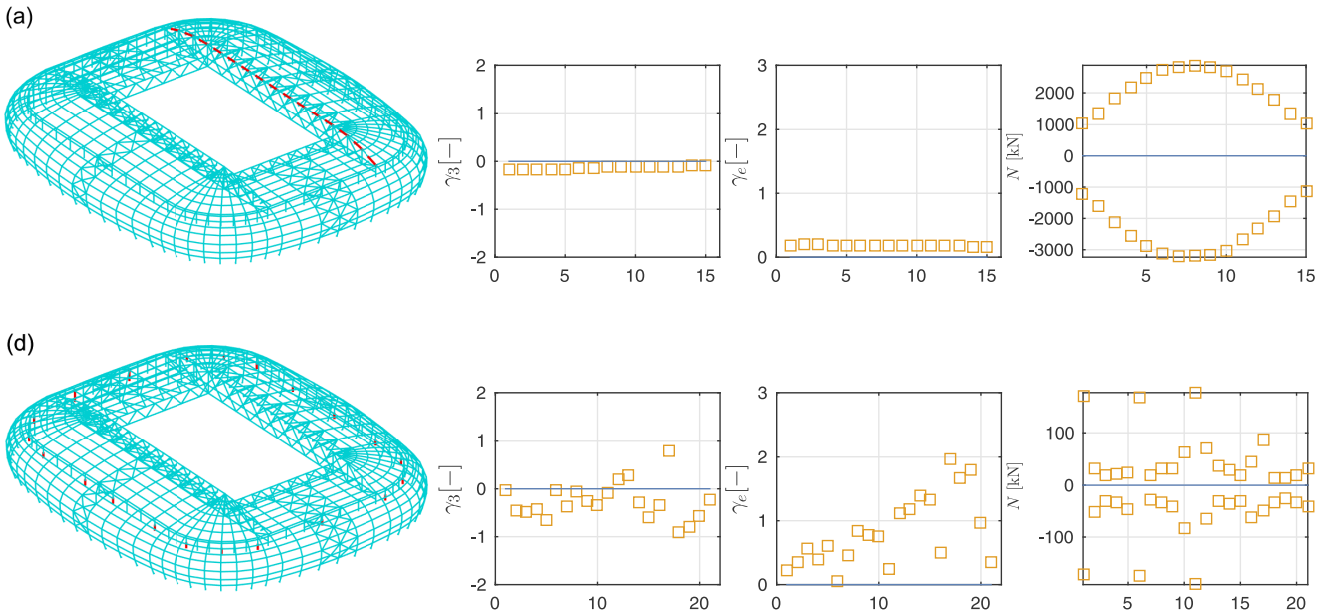
Updating the PSWL basis (Automatic procedure)

Non-Gaussian framework



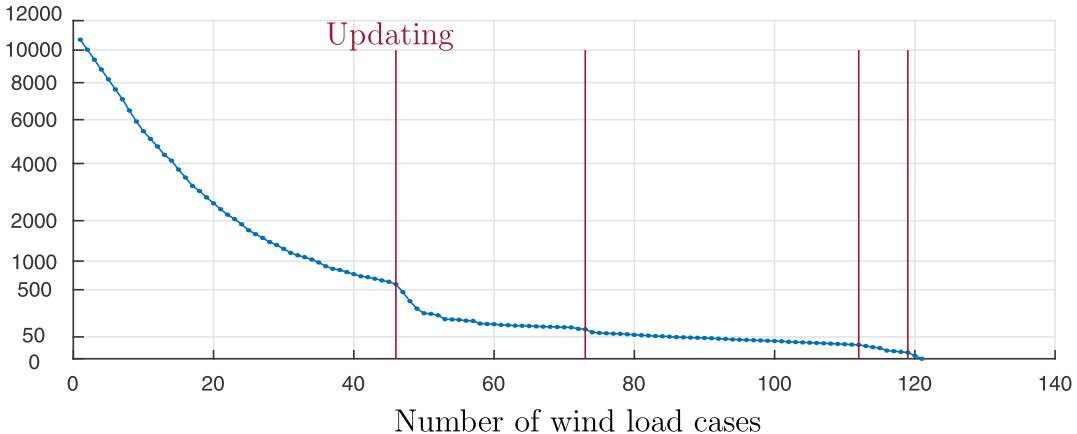
Envelope reconstruction problem

- Non-Gaussian envelope values



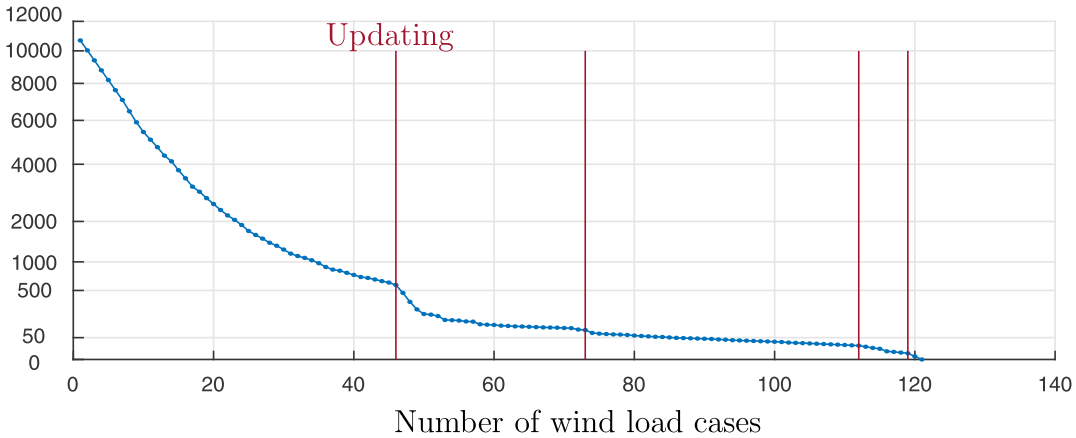
Envelope reconstruction problem

- Number of responses (out of 15988) outside the tolerance [0,+25%]

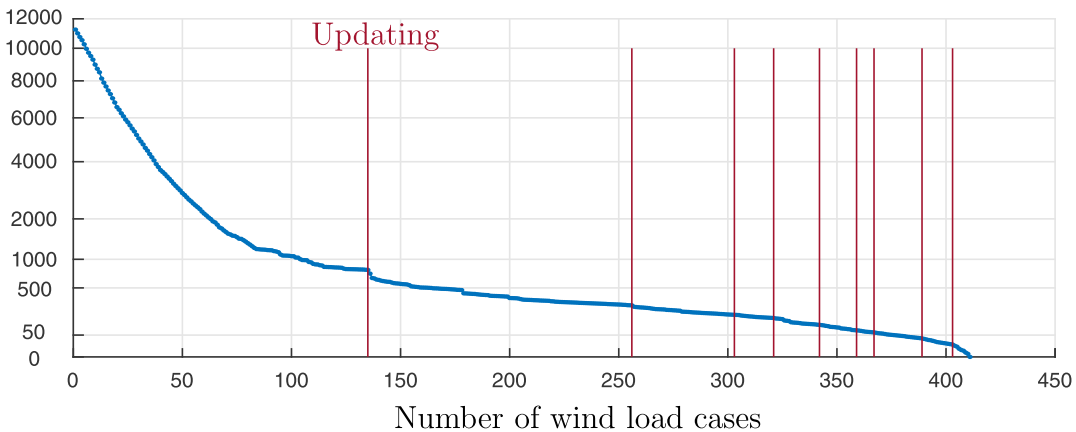


Envelope reconstruction problem

- Number of responses (out of 15988) outside the tolerance [0,+25%]

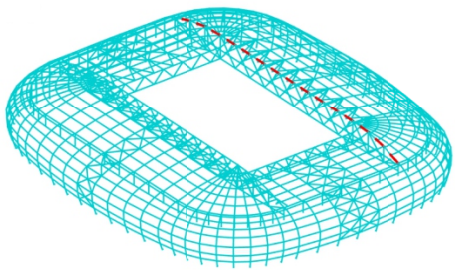


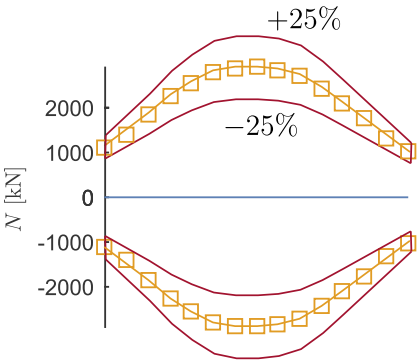
- Number of responses (out of 15988) outside the tolerance [0,+10%]



How to establish static wind loads for large civil structures?

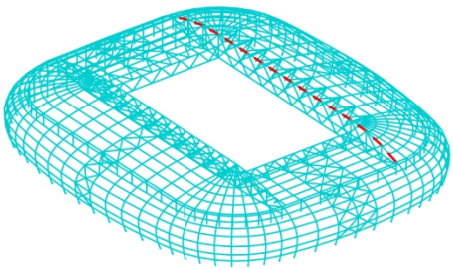
- Envelope reconstruction problem formulation

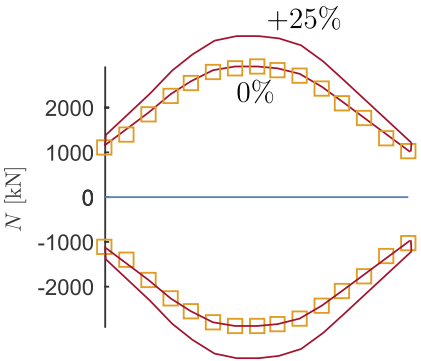




How to establish static wind loads for large civil structures?

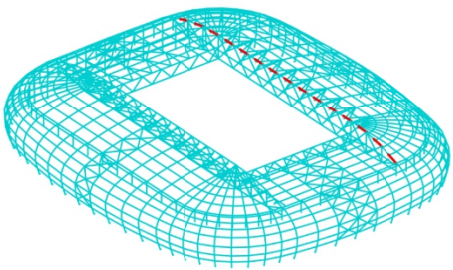
- Envelope reconstruction problem formulation

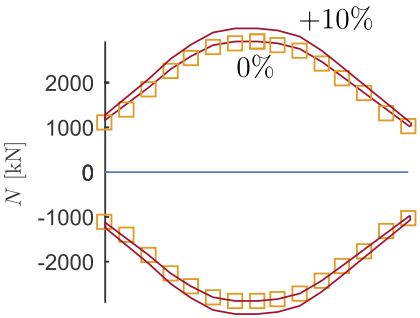




How to establish static wind loads for large civil structures?

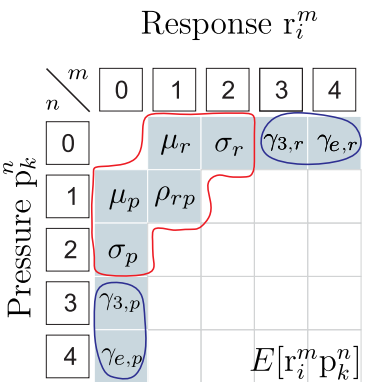
- Envelope reconstruction problem formulation





How to establish static wind loads for large civil structures?

- Envelope reconstruction problem formulation
- Conditional Expected Static Wind Loads

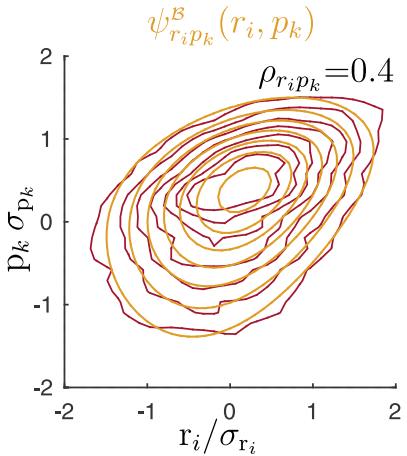


Gaussian assumption

Bicubic Model

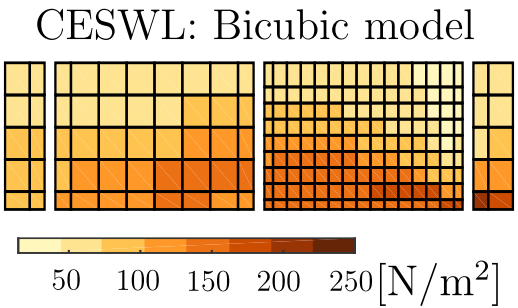
How to establish static wind loads for large civil structures?

- Envelope reconstruction problem formulation
- Conditional Expected Static Wind Loads



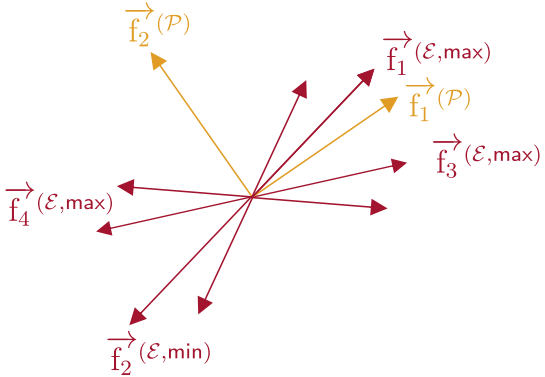
How to establish static wind loads for large civil structures?

- Envelope reconstruction problem formulation
- Conditional Expected Static Wind Loads



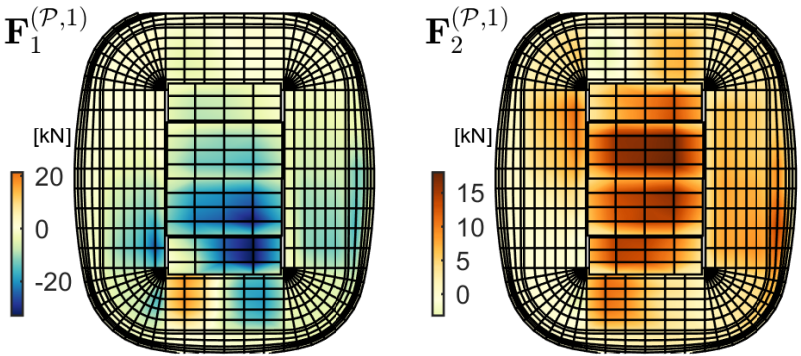
How to establish static wind loads for large civil structures?

- Envelope reconstruction problem formulation
- Conditional Expected Static Wind Loads
- Principal Static Wind Loads



How to establish static wind loads for large civil structures?

- Envelope reconstruction problem formulation
- Conditional Expected Static Wind Loads
- Principal Static Wind Loads

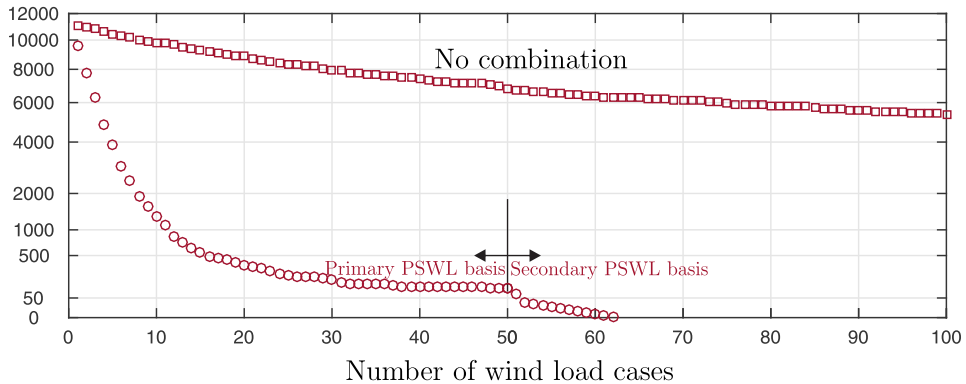


How to establish static wind loads for large civil structures?

- Envelope reconstruction problem formulation
- Conditional Expected Static Wind Loads
- Principal Static Wind Loads
- Combinations of Principal Static Wind Loads

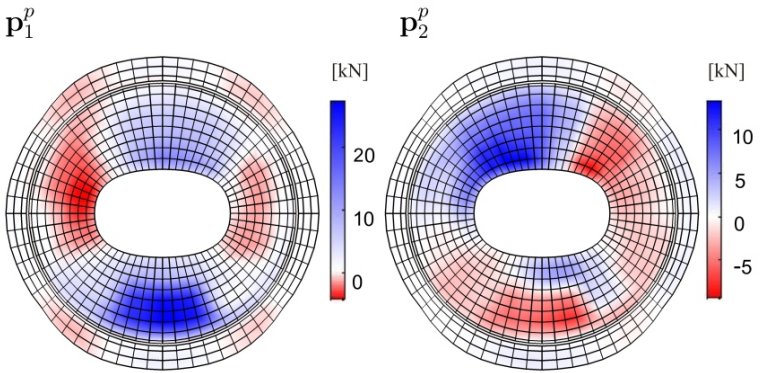
How to establish static wind loads for large civil structures?

- Envelope reconstruction problem formulation
- Conditional Expected Static Wind Loads
- Principal Static Wind Loads
- Combinations of Principal Static Wind Loads
- Updating of Principal Static Wind Loads

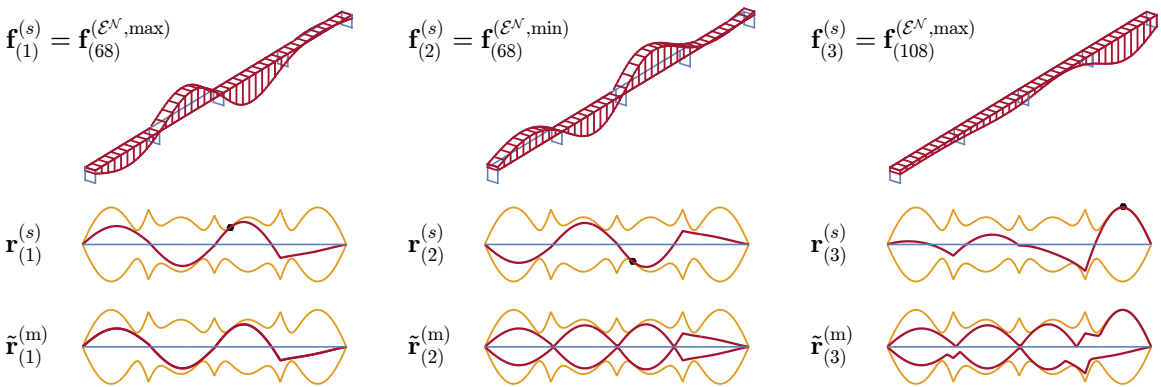


PSWLs applied to other structures

- Marseille's velodromme

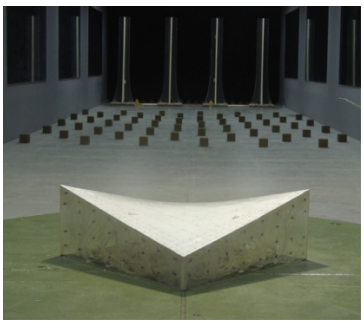


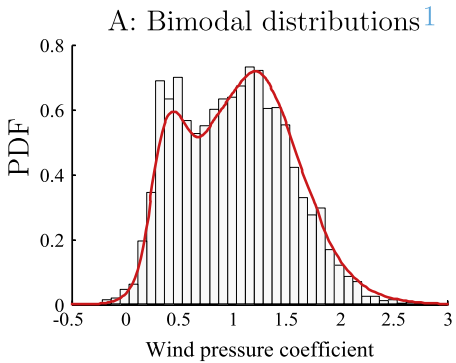
- Four span-Bridge under lift aerodynamic forces

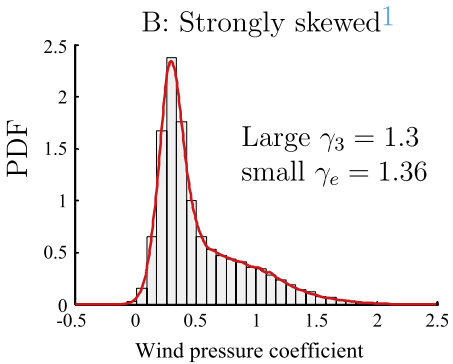


Perspectives

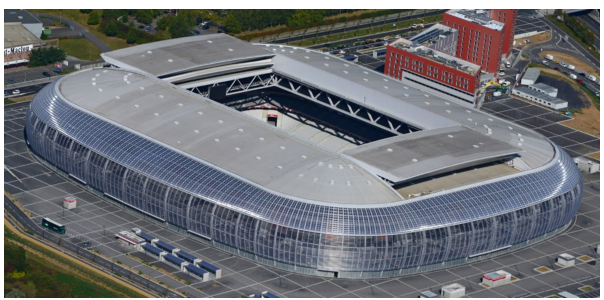
- Conditional Expected Static Wind Load (Non-Gaussian context)
  - Bimodal random processes, Softening random processes
  - Maximum entrop method, Conditional kernel density estimation, ...

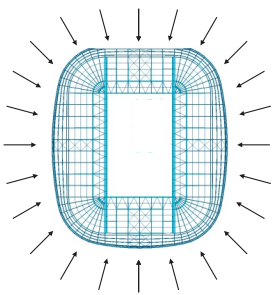






- Structural wind design: several wind directions





1 Ding J., Chen X. (2014). Assessment of methods for extreme value analysis of non-Gaussian wind effects with short-term time history samples. (adapted figures)

Perspectives

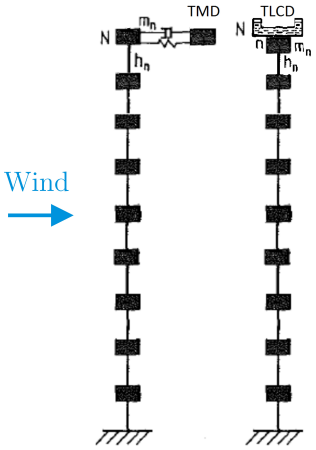
- Non-synoptic winds: Transient phenomena

Downburst

Thunderstorm

Tornado

- Non-linear (elastic) structural behavior
  - TLCD: Mitigation of the along-wind response of tower



Perspectives

- Static wind loads for long-span bridges

Golden Gate Bridge (2737m), USA

Viaduc de Millau (2460m), France

Perspectives

- Static wind loads for high-rise buildings (skyscrapers)

Petronas twin towers (451m)

Shanghai World financial (492m)

Taipei 101 (509m)

Burj Khalifa (828m)

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  - Gare des guillemins: https://www.flickr.com/photos/sixteen-miles/4305809704/lightbox/
- Slide: Various wind systems
  - https://en.wikipedia.org/wiki/Supercell
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