# Principal Static Wind Loads
# for the envelope reconstruction problem

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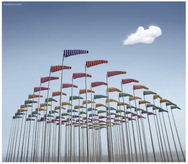
# Analysis of structures under random excitations

## Structures

## are subjected to random excitations



## and we have to solve the equation of motion

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{p}(t)$$

Mass, Damping, Stiffness, Nodal displacements, External forces

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# Design envelope

Representative extreme values of structural responses
⟶ **Design envelope**

Wind actions ⟶ Structural linear analysis ⟶ Structural Gaussian responses

**Wind actions**
- Time/Space evolution
- Power Spectral Density
- Coherence function
- ...

**Structural linear analysis**
- Step-by-step method
- Spectral analysis
- Nodal/Modal basis
- Background/Resonant decomposition

**Structural Gaussian responses**
- $\mathbf{r}^d(t) = \boldsymbol{\mu}_r + \mathbf{r}(t)$

# Design envelope

**Representative extreme values of structural responses $\longrightarrow$ Design envelope**

Wind actions → Structural linear analysis → Structural Gaussian responses

**Wind actions**

— Time/Space evolution
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— ...

**Structural linear analysis**

— Step-by-step method
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**Structural Gaussian responses**

— $\mathbf{r}^d(t) = \boldsymbol{\mu}_r + \mathbf{r}(t)$

— Envelope $(\mathbf{r}^{min}; \mathbf{r}^{max})$

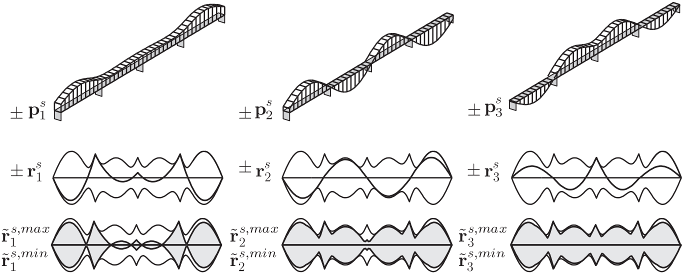
$$\mathbf{r}^{min} = -g\boldsymbol{\sigma}_r \;\; ; \;\; \mathbf{r}^{max} = g\boldsymbol{\sigma}_r$$

— Design envelope $(\mathbf{r}^{d,min}; \mathbf{r}^{d,max})$

$$\mathbf{r}^{d,min} = \boldsymbol{\mu}_r + \mathbf{r}^{min}$$
$$\mathbf{r}^{d,max} = \boldsymbol{\mu}_r + \mathbf{r}^{max}$$

# Structural design


**Do static loadings that reproduce efficiently this envelope exist ?**




$$\tilde{\mathbf{r}}_k^{s,min} = min\left(\tilde{\mathbf{r}}_{(k-1)}^{s,min}; \mathbf{r}^s; -\mathbf{r}^s; 0\right) \quad ; \quad \tilde{\mathbf{r}}_k^{s,max} = max\left(\tilde{\mathbf{r}}_{(k-1)}^{s,max}; \mathbf{r}^s; -\mathbf{r}^s; 0\right)$$

**Envelope reconstruction problem**

# Envelope reconstruction problem

## Objective :

Derive a suitable basis of $\mathbf{p}^s$ for the *envelope reconstruction problem*

## Proposed solutions :

- Global loading technique (Repetto & Solari, 2004)[1]
- Universal loads (Katsumura et al., 2007)[2]
- Proper-orthogonal decomposition of wind loads (Fiore & Monaco, 2009)[3]
- Least-squares fitting (Zhou et al., 2011)[4]

## Possible improvements

- automatic procedure ; robustness ; take into account the structural behaviour of the structure ; no tuning of parameters

[1] Repetto M.P., Solari G. (2004). Equivalent static wind actions on vertical structures. *Journal of Wind Engineering and Industrial Aerodynamics* 92, 335-357.

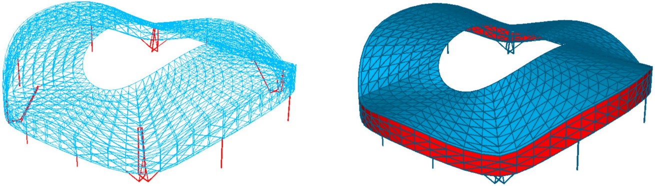
[2] Katsumura A., Tamura Y., Nakamura O. (2007). Universal wind load distribution simultaneously reproducing largest load effects in all subject members on large-span cantilevered roof. *Int. J. Wind Eng. Ind. Aerod.* 95 (9-11), pp. 1145-1165

[3] Fiore A., Monaco P. (2009). Pod-based representation of the alongwind equivalent static force for long-span bridges. *Wind and Structures*, 12 (3), pp. 239-257.

[4] Zhou X., Gu M., Li G. (2011). Application research of constrained least-squares method in computing equivalent static wind loads. *In : Proceeding of the 13th International Conference on Wind Engineering*.

# Description of the structure

Computed graphic of Marseille's velodrome, France[1]

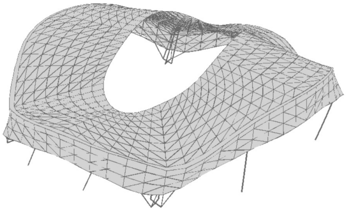


Structural finite element model (Greisch, Liège)[2]

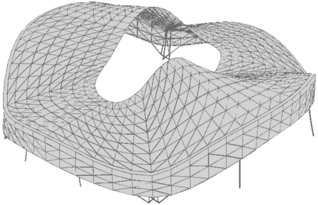
[1] http ://www.arema-velodrome.com/ [2] http ://www.greisch.com/

# Description of the structure

- Modal characteristics (FineLg[1])



Mode 1



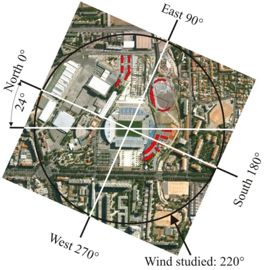
Mode 3

| Mode | $f_{nat}[Hz]$ | $\mathbf{K}^*$(kN/m) | $\mathbf{M}^*(t)$ | Description |
|---|---|---|---|---|
| 1 | 0.659 | 42898 | 2500 | global horizontal displacement |
| 2 | 0.831 | 60890 | 2232 | global horizontal displacement |
| 3 | 0.920 | 20820 | 623 | antisymmetric horizontal displacement |
| 4 | 0.958 | 25581 | 706 | global vertical displacement |

[1] FineLg. (2003), Non linear finite element analysis program : User's Manual, Unveristy of Liège, ArGEnCo and Greisch Ingènierie.

# Wind tunnel simulation

- Aerodynamic loading characterization



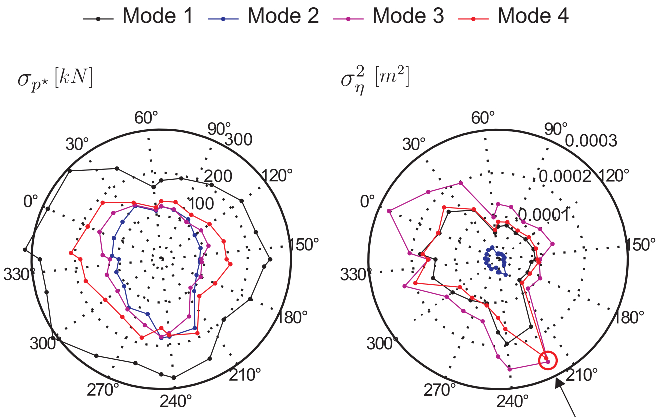

1/250-scaled model (rigid) of the stadium and map view[1]

- Measurement characteristics
  - 22 tested wind directions
  - number of sensors : ∼500
  - sampling frequency of 2.2 Hz ! (full scale model)
  - measurement period : 105 min (full scale model)

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

# Buffeting wind analysis

- Nodal Background/Modal Resonant Spectral analysis[1]




→ Studied wind direction : 220°

[1] More information are given in the full length paper

Introduction

Studied structure

**Envelope reconstruction problem**

Results

Conclusion

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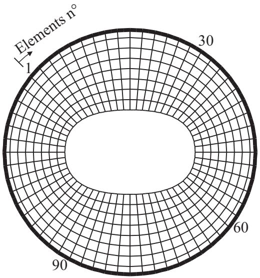
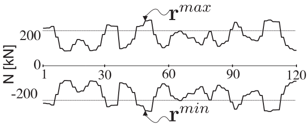
# Definition of the target envelope

- Beam elements in the structure : 5736
- **Target envelope** collects the six internal forces for each beam element :
  - Axial force ; two bending moments ; two shear forces ; torque.
  - Number of structural responses : 68832

- Illustration of the envelope reconstruction
  - Axial force of 120 beam elements




  - Reconstruction of the full envelope is illustrated in the paper

# Equivalent Static Wind Loads

- An **Equivalent** Static Wind Load (ESWL) ⇔ **one specific** extreme structural response (out of the 68832)
  - Nodal background analysis : Load-response-correlation method (Kasperski, 1991)[1]
  - Nodal background and modal resonant analysis (Chen & Kareem, 2001)[2]
  - Full nodal analysis (Blaise & Denoël, 2012)[3]

- **ESWL matrix $\mathbf{P}^e$**
  - All investigated structural responses $(N = 68832)$
  - ESWLs are derived with the method by Chen & Kareem

$$\mathbf{P}^e = \underbrace{\begin{pmatrix} p^e_{11} & \cdots & p^e_{1N} \\ \vdots & \ddots & \\ p^e_{m1} & & p^e_{mN} \end{pmatrix}}_{m \times N}$$

[1] Kasperski M. (1992). Extreme wind load distributions for linear and nonlinear design *Engineering Structures* 14, 27-34.
[2] Chen X.Z., Kareem A. (2001). Equivalent static wind loads for bueting response of bridges. *Journal of Structural Engineering-Asce* 127, 1467-1475.
[3] Blaise N., Denoël V. (2012). Principal Static Wind Loads. *Int. J. Wind Eng. Ind. Aerod.*, Under review (Unpublished).

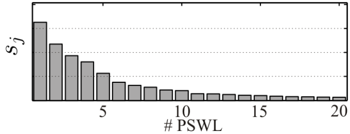
# Principal Static Wind Loads

- **Key-idea** : Singular value decomposition of the **ESWL matrix** $\mathbf{P}^e$

$$\underbrace{\begin{pmatrix} p^e_{11} & \cdots & p^e_{1N} \\ \vdots & \ddots & \\ p^e_{l1} & & p^e_{lN} \end{pmatrix}}_{l \times N}^{\mathbf{p}^e} = \underbrace{\begin{pmatrix} p^p_{11} & \cdots & p^p_{1M} \\ \vdots & \ddots & \\ p^p_{l1} & & p^p_{mM} \end{pmatrix}}_{l \times M}^{\mathbf{p}^p} \underbrace{\begin{pmatrix} s_{11} & & 0 \\ & \ddots & \\ 0 & & s_{MM} \end{pmatrix}}_{M \times M}^{\mathbf{s}} \underbrace{\begin{pmatrix} v_{11} & \cdots & v_{1N} \\ \vdots & \ddots & \\ v_{M1} & & v_{MN} \end{pmatrix}}_{M \times N}^{\mathbf{v}'}$$

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

**Convergence of the decomposition → $\mathbf{M} \simeq \mathbf{15} \lll \mathbf{N} = \mathbf{68832}$**



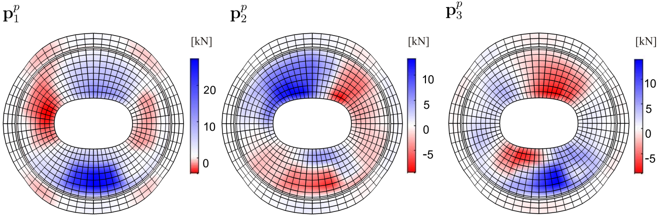

[1] Blaise N., Denoël V. (2012). Principal Static Wind Loads. *Int. J. Wind Eng. Ind. Aerod.*, Under review

# Principal Static Wind Loads

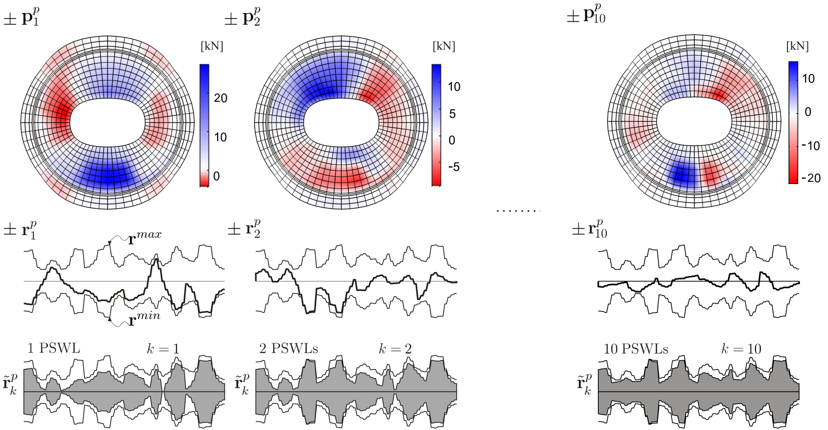
## A solution

**Use of the PSWL basis for the *envelope reconstruction problem***

- PSWLs are not associated with specific structural responses (global responses)
- PSWLs are well-suited for combinations $\mathbf{P}^s = \mathbf{P}^p \mathbf{q}^p$
- PSWL basis is built with an automatic procedure
- PSWLs are scaled such that there is no-overestimation of the real envelope (tangency condition)



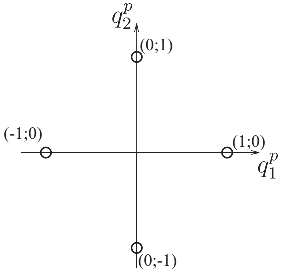
# PSWLs and the corresponding responses



# PSWLs and the corresponding responses

- No combination

M=2 PSWLs

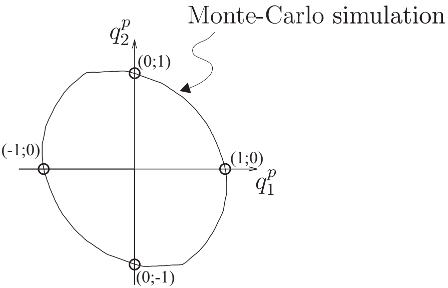



○ No combination $2^M$

# Combinations of the PSWLs

- Monte-Carlo simulation+ tangency condition

M=2 PSWLs

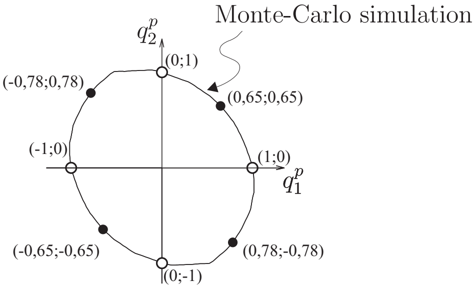



○ No combination $2^M$

# Combinations of the PSWLs

- Considered combinations + tangency condition

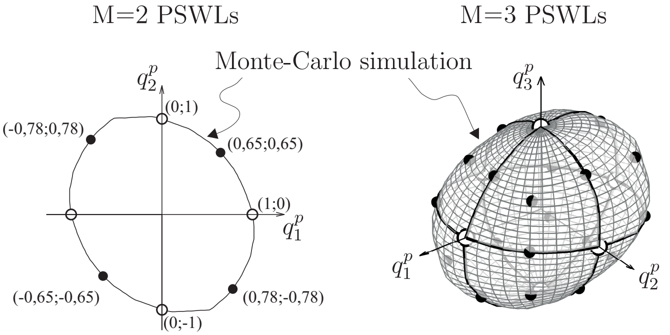
M=2 PSWLs




○ No combination $2^M$ ○,● Considered combinations $3^M - 1$

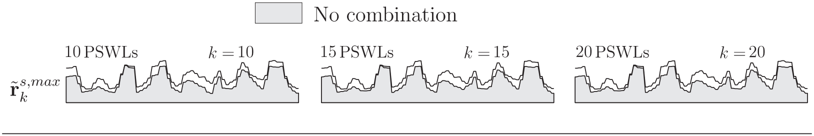
# Combinations of the PSWLs

- Extension : three first PSWLs

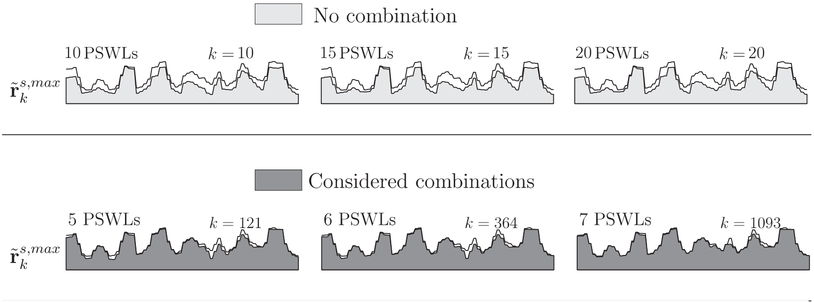



○ No combination $2^M$ ○,● Considered combinations $3^M - 1$

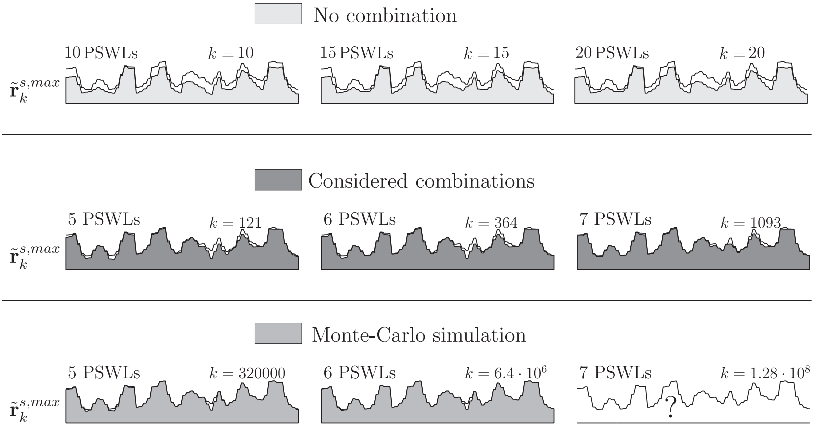
# Combinations of the PSWLs



# Combinations of the PSWLs



# Combinations of the PSWLs

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## Selection of design wind loads

- **Structural design**
  - truncation of the PSWL basis ($M = ?$)
  - definition of the available (predefined) set of combinations ($\mathbf{q}^p = ?$)
  - selection of a small number of representative static wind loads ($k = ?$)
- **Maximization of a chosen indicator of convergence**

$$\boxed{\Psi_k = f\left(\tilde{\mathbf{r}}_{k-1}, \mathbf{r}, \mathbf{p}^p, \mathbf{q}^p\right)}$$

  - function of the $k-1^{th}$ reconstructed envelope $\tilde{\mathbf{r}}_{k-1}$
  - target envelope $\mathbf{r}$
  - considered principal loadings $\mathbf{p}^p$ and combinations thereof $\mathbf{q}^p$
- **Illustration in the full length paper**[1]

[1] Blaise N., Hamra Lotfi, Denoël V. (2012). Principal Static Wind Loads on a large roof structure. In : Proceeding of the In Vento Conference, Venizia.

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Derive a suitable basis of $\mathbf{p}^s$ for the *envelope reconstruction problem*
→ **Principal Static Wind Loads**

- **Main characteristics**
  - Obtained by an automatic procedure (**SVD**) → Robust
  - Minimum number of principal loadings is necessary
  - Represent global loadings
  - Well-suited for combinations
  - Possible codification
- **Comparison**[1] : Loadings obtained from Covariance Proper Transformation
- **Assumptions** : linear analysis and gaussian responses
- **Perspective** : non gaussian responses

[1] Blaise N., Denoël V. (2012). Principal Static Wind Loads. *Int. J. Wind Eng. Ind. Aerod.*, Under review

Thank you for your attention.

Questions ?

Read out more about me on : www.orbi.ulg.ac.be

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