Envelope Reconstruction with Equivalent Wind Loads

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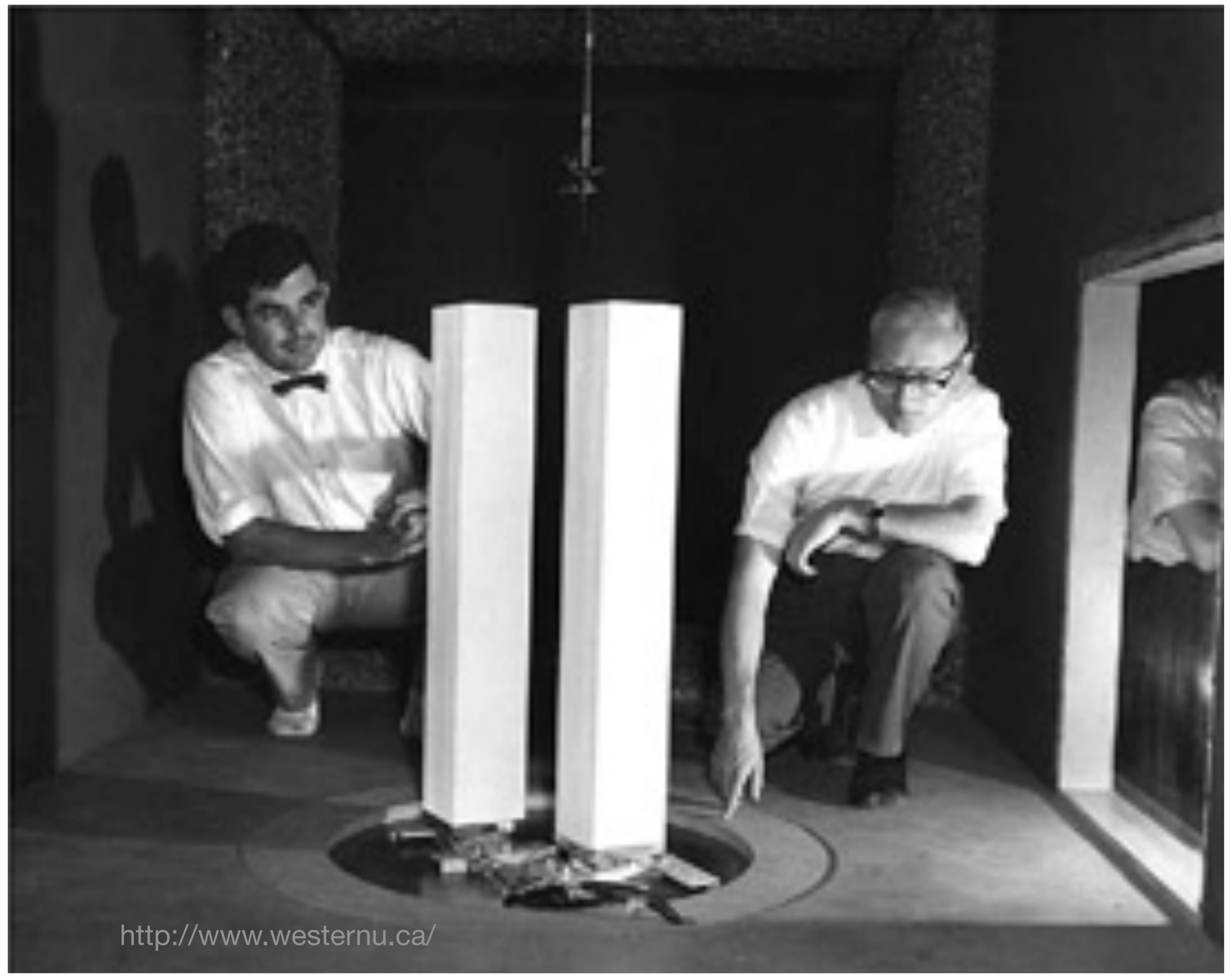
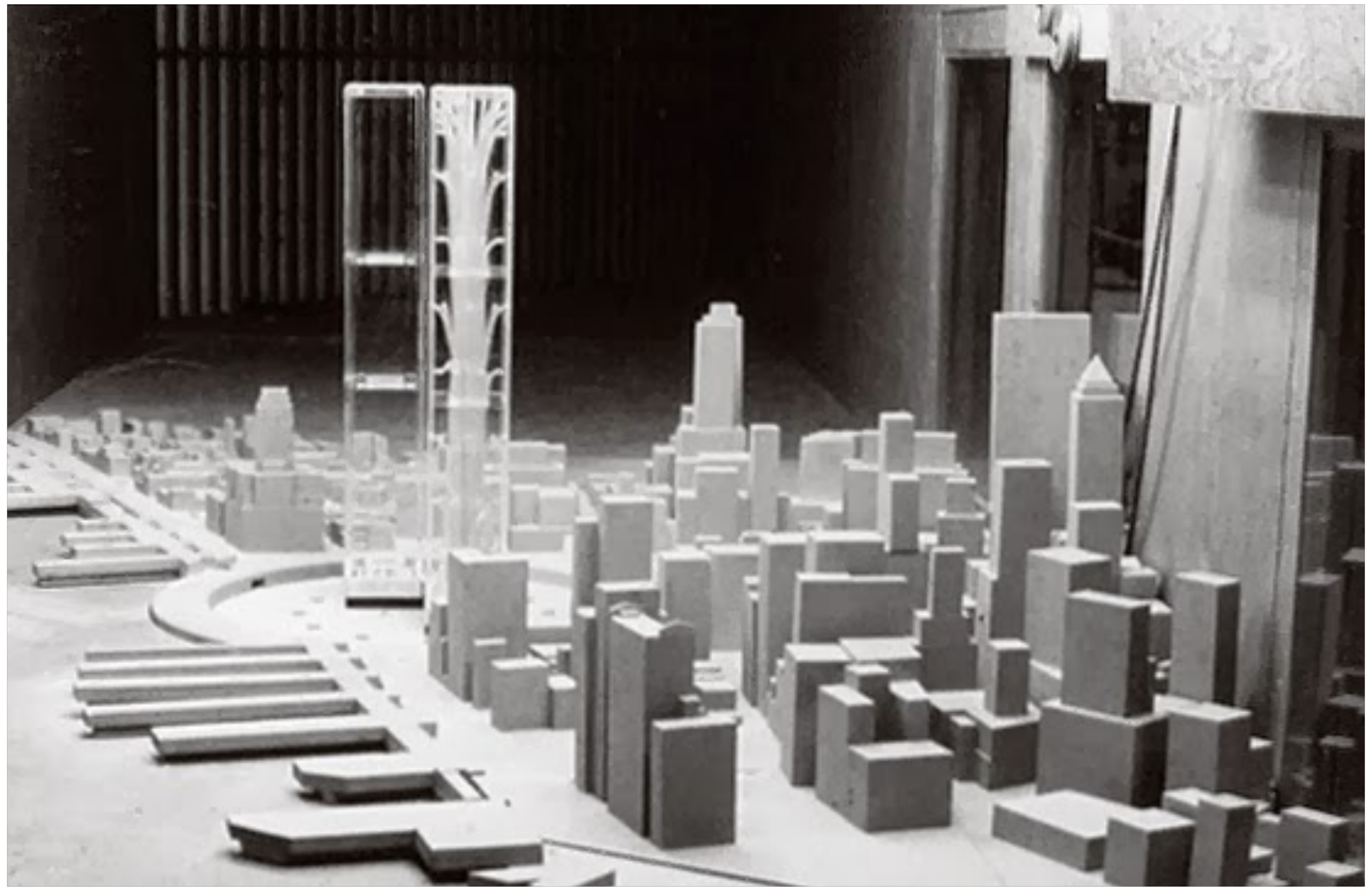
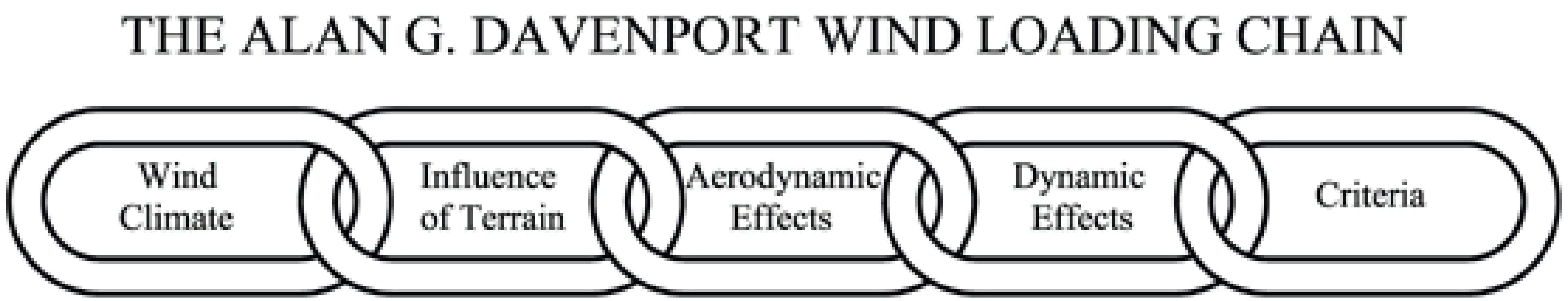
Buffeting analysis

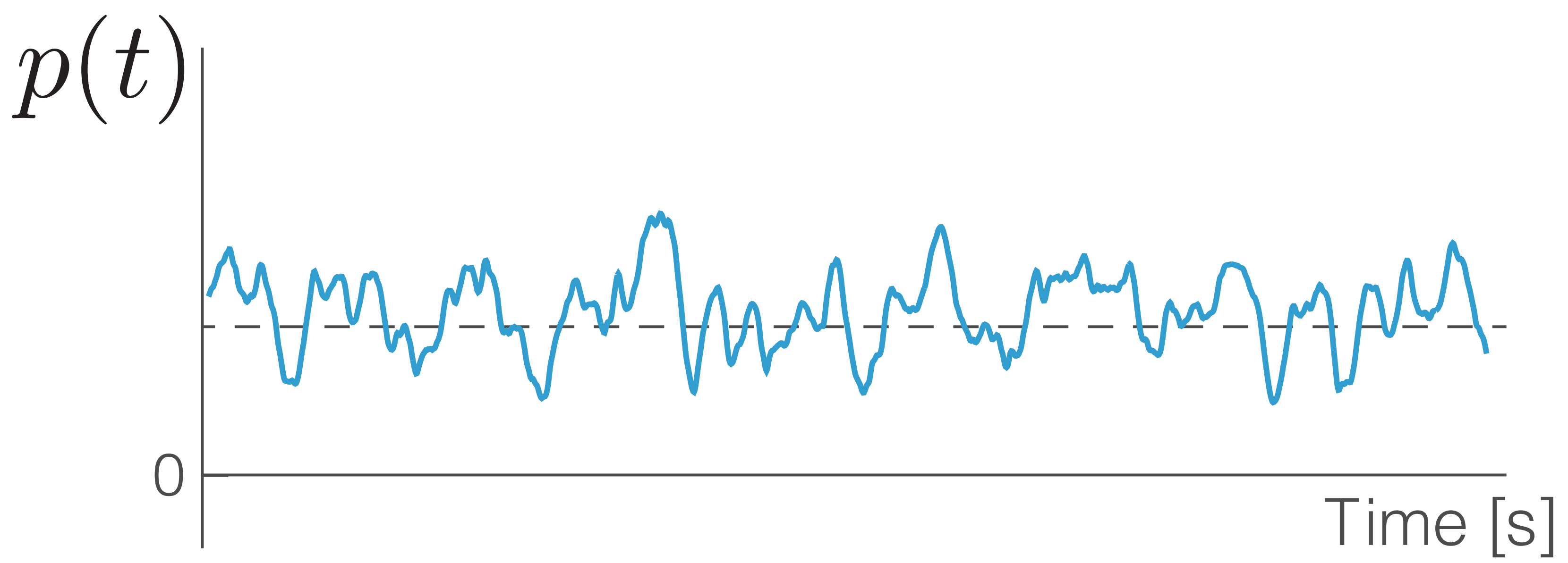




1964: Wind Tunnel Testing World Trade Center (Drs. J. E. Cermak and A.G. Davenport in the Colorado State University boundary layer wind tunnel)

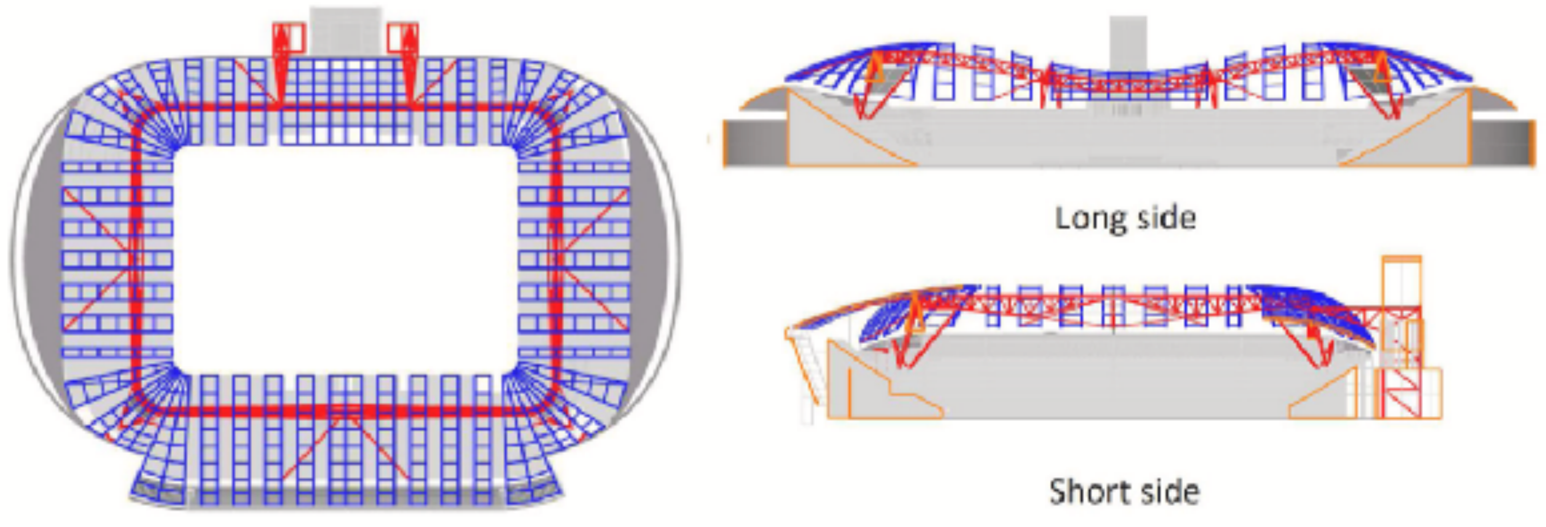


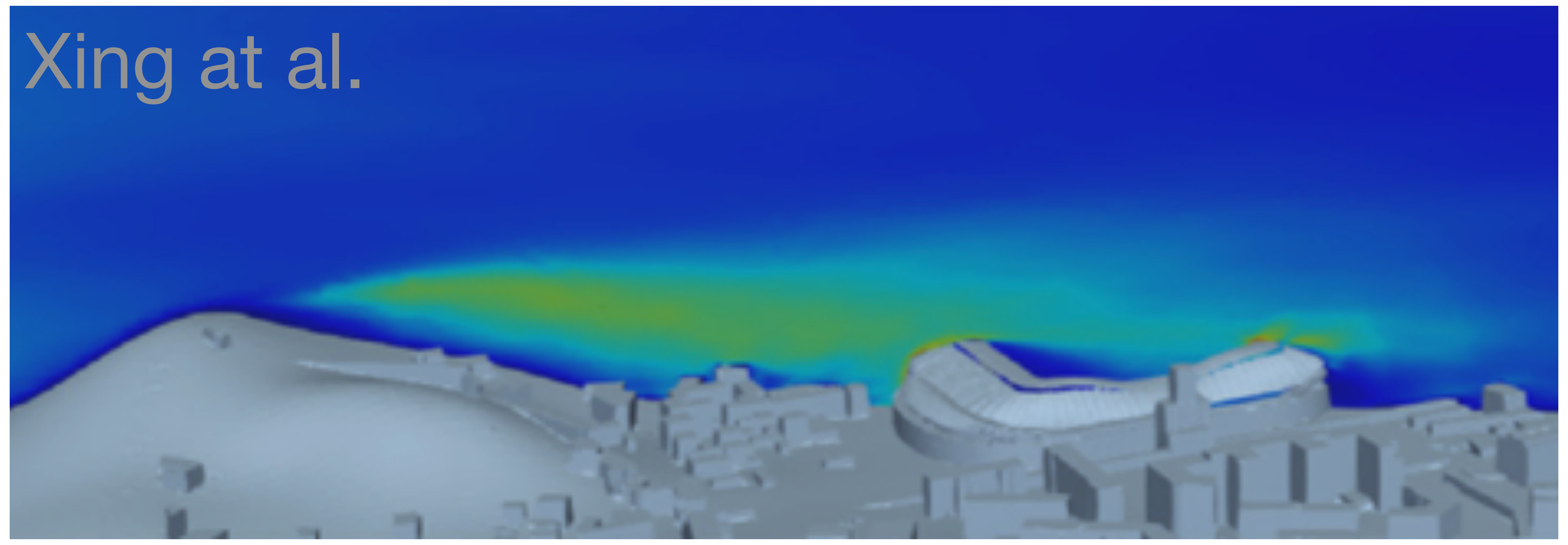
The two approaches to wind loads on complex structures



Wind tunnel testing

NF WD ISO
IEC
TR
EN FDIS

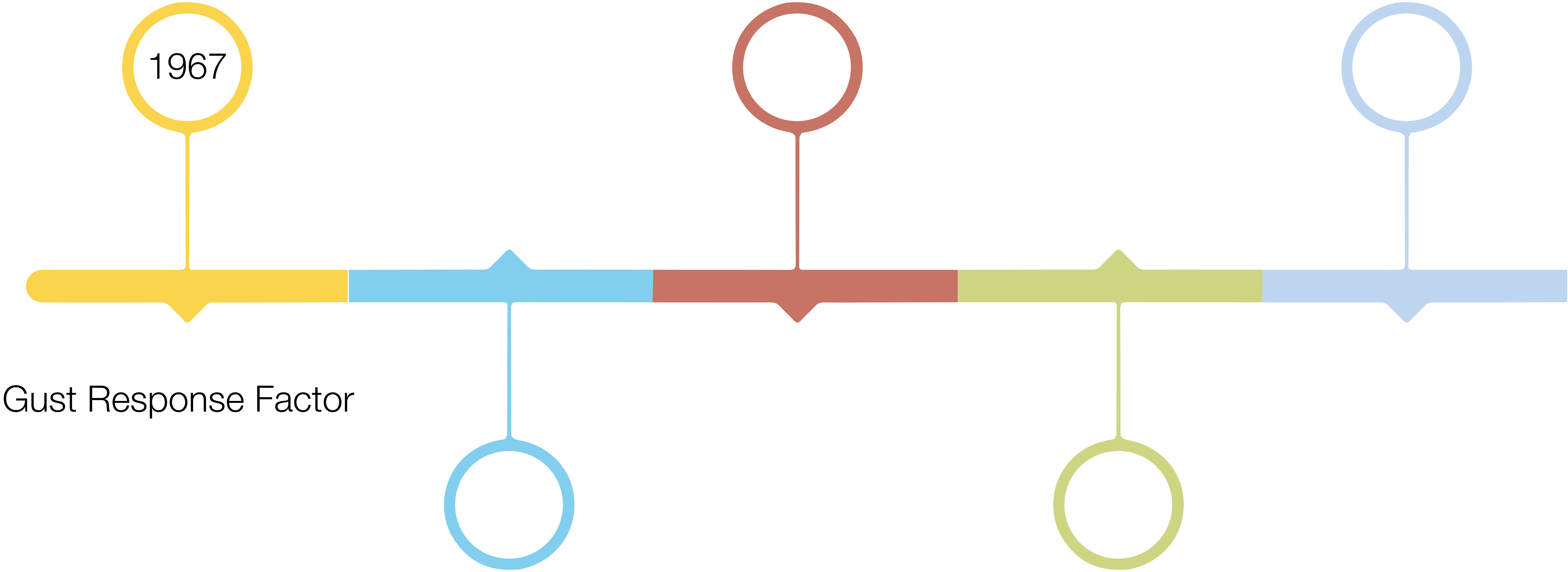




Computational Fluid Dynamics

Part I : Equivalent Static Wind Loads

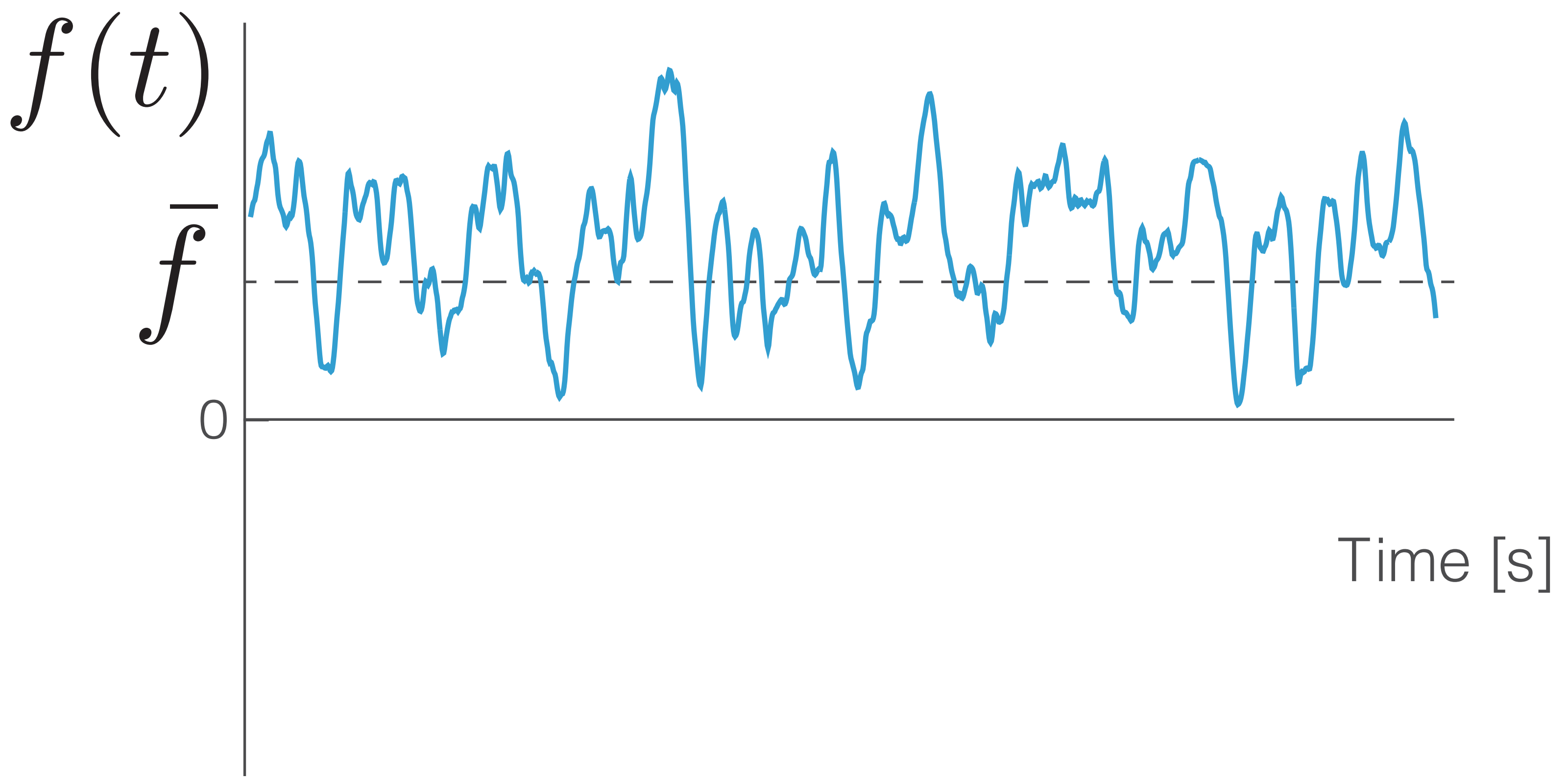
Timeline



Davenport, 1964-1967

Simple introductory examples

1-DOF Mass-spring oscillator - drag only

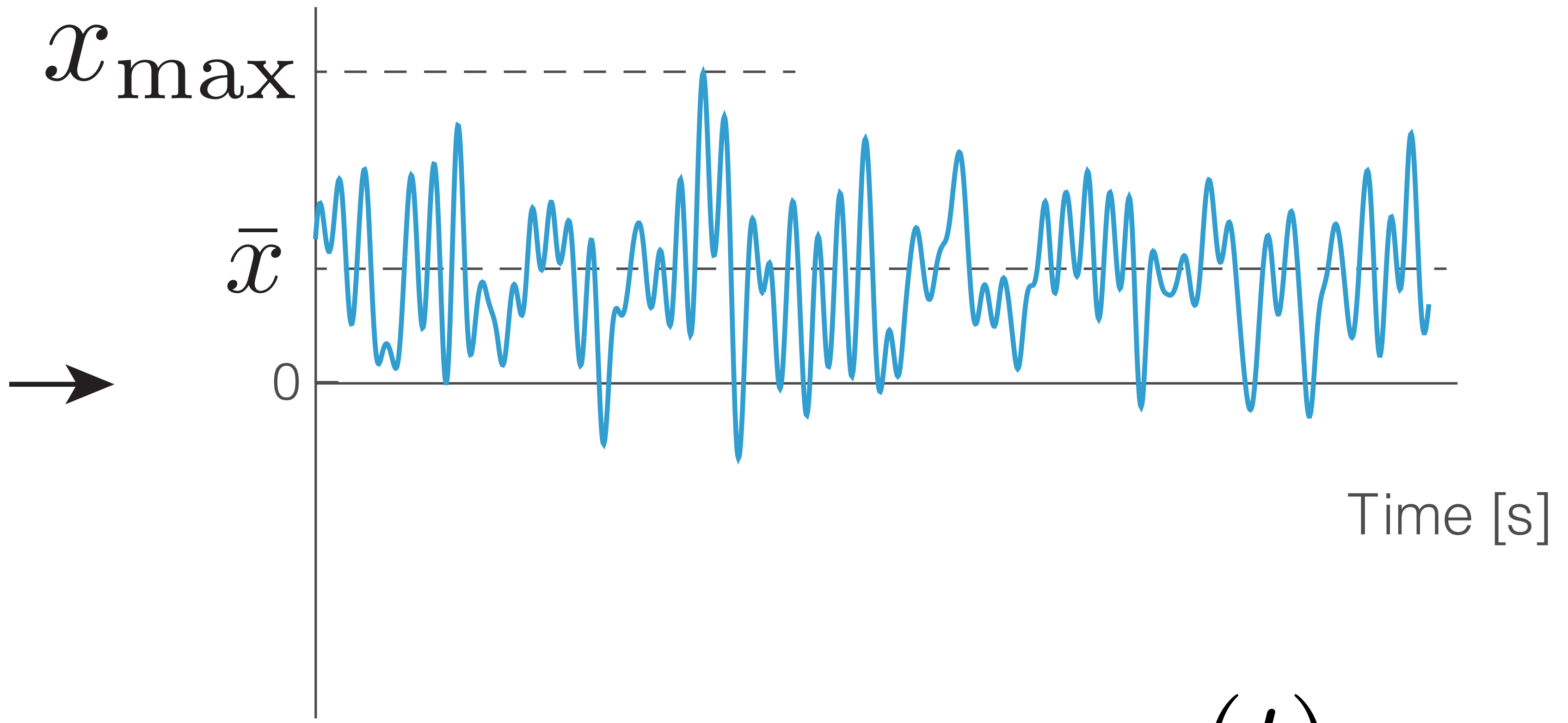


→

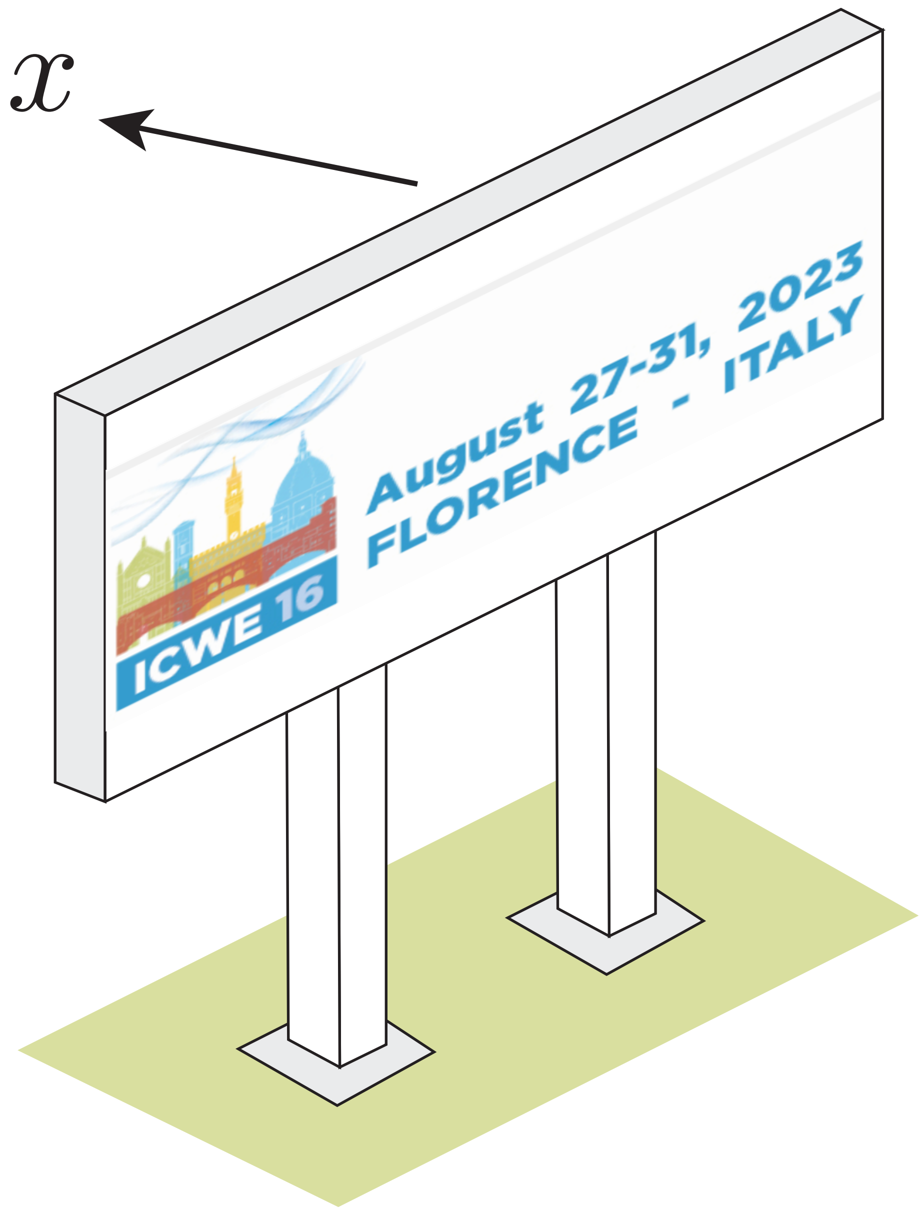
dynamic

$$m\ddot{x} + c\dot{x} + kx = f(t)$$

→



$$x_{\max} = \max_t x(t)$$



static $$kx_{\max} = f_{\mathrm{E}}$$

avoid ?

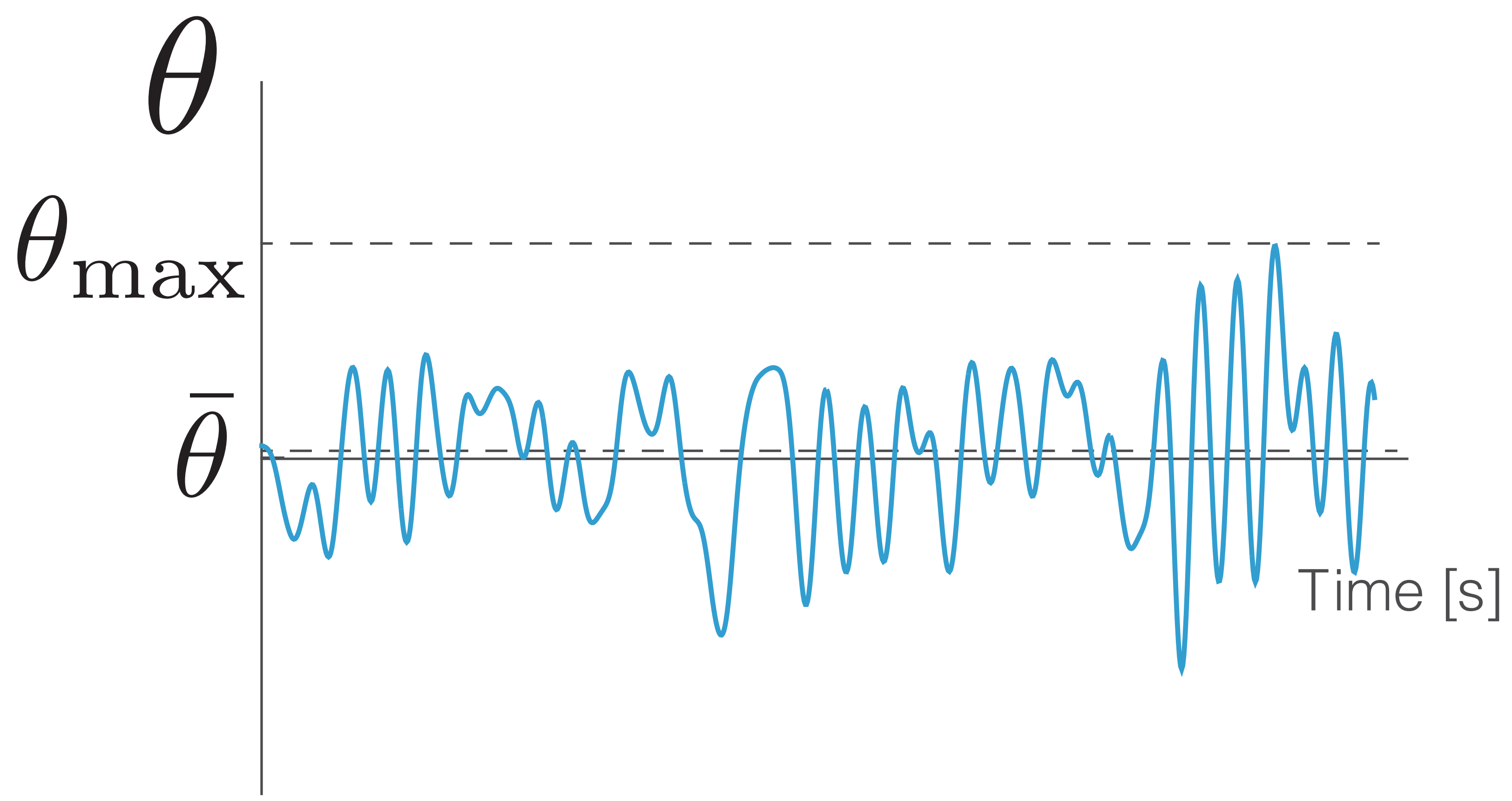
$$x_{\max} = \bar{x} + \Delta x_{\max} = \bar{x} + g\,\sigma_x$$

$$x_{\max} = \bar{x}\left(1 + g\,\frac{\sigma_x}{\bar{x}}\right) = \mathrm{GRF}\,\bar{x}$$

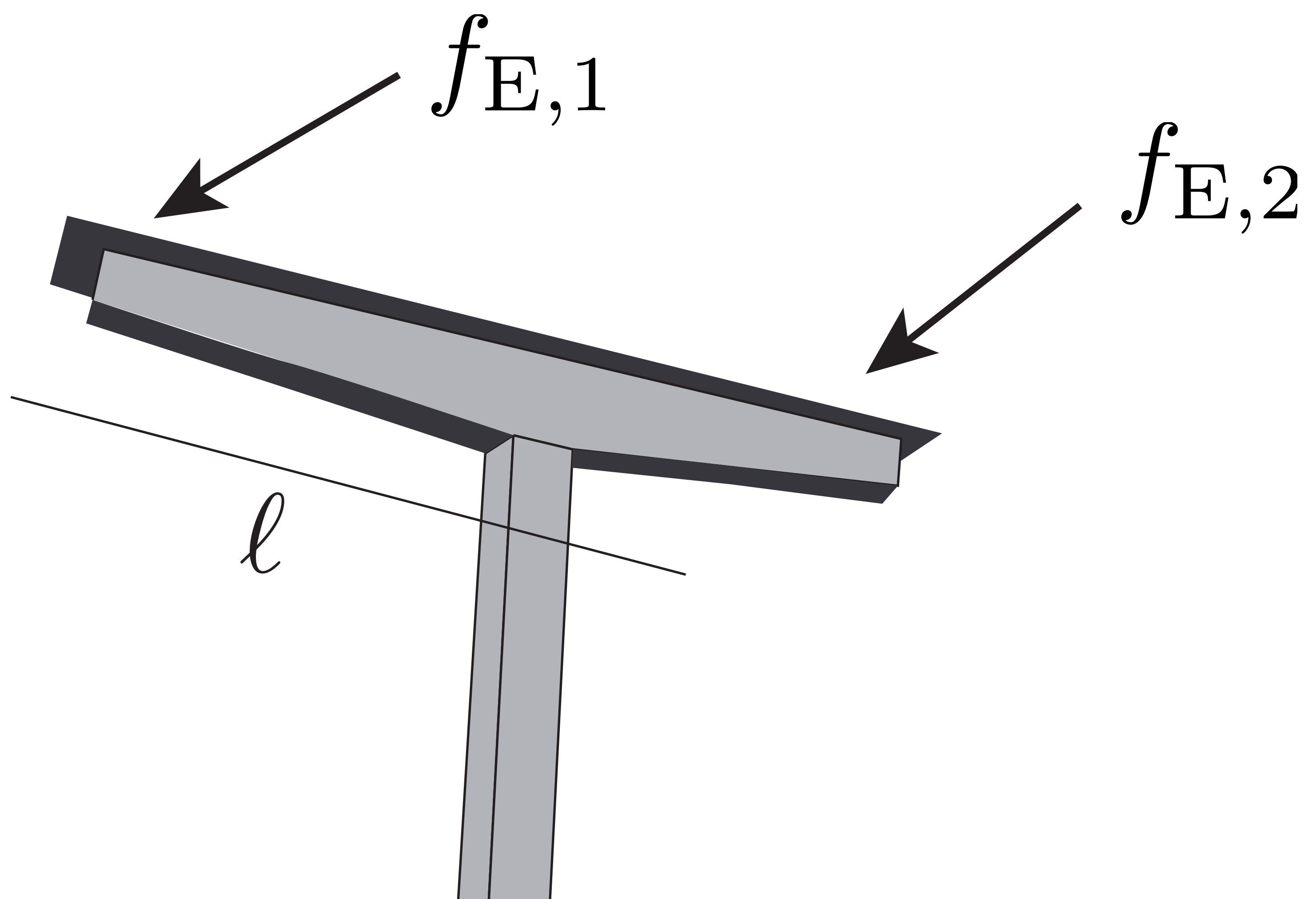
$$f_{\mathrm{E}} = k\,x_{\max} = \mathrm{GRF}\,k\bar{x} = \mathrm{GRF}\,\bar{f}$$

Simple introductory examples

1-DOF torsional oscillator (balanced cantilever bridge)



$$\frac{k_T}{\ell}\theta_{\max} = f_{E,2} - f_{E,1}$$



To use $\mathbf{f}_E \propto \bar{\mathbf{f}}$ doesn't work anymore !

GRF fails if small or zero average

However, we could use $f_{E,2} \neq f_{E,1}$ to create a torsional response

1-DOF torsional oscillator (balanced cantilever bridge)

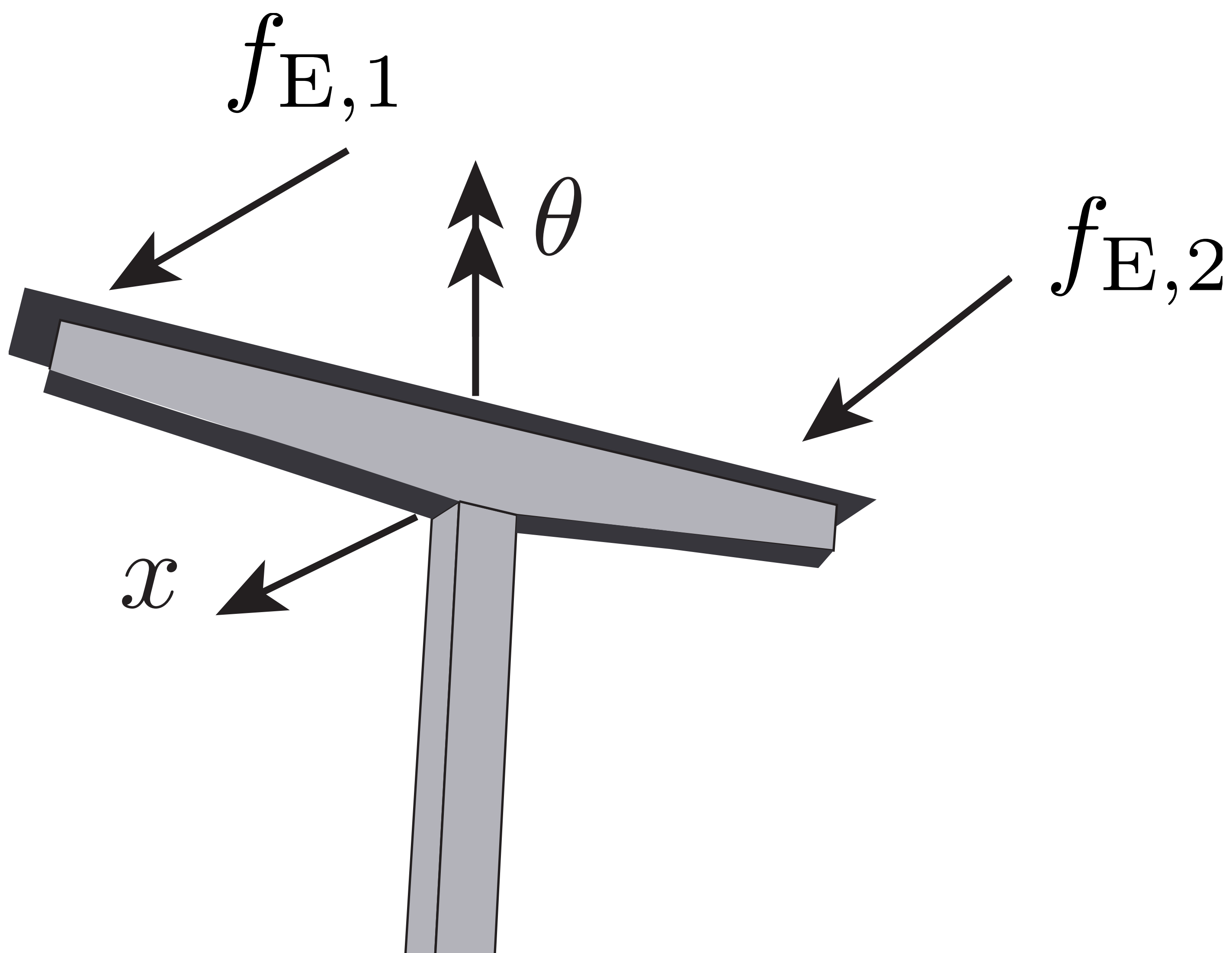
$$\frac{k_T}{\ell}\theta_{\max} = f_{E,2} - f_{E,1}$$

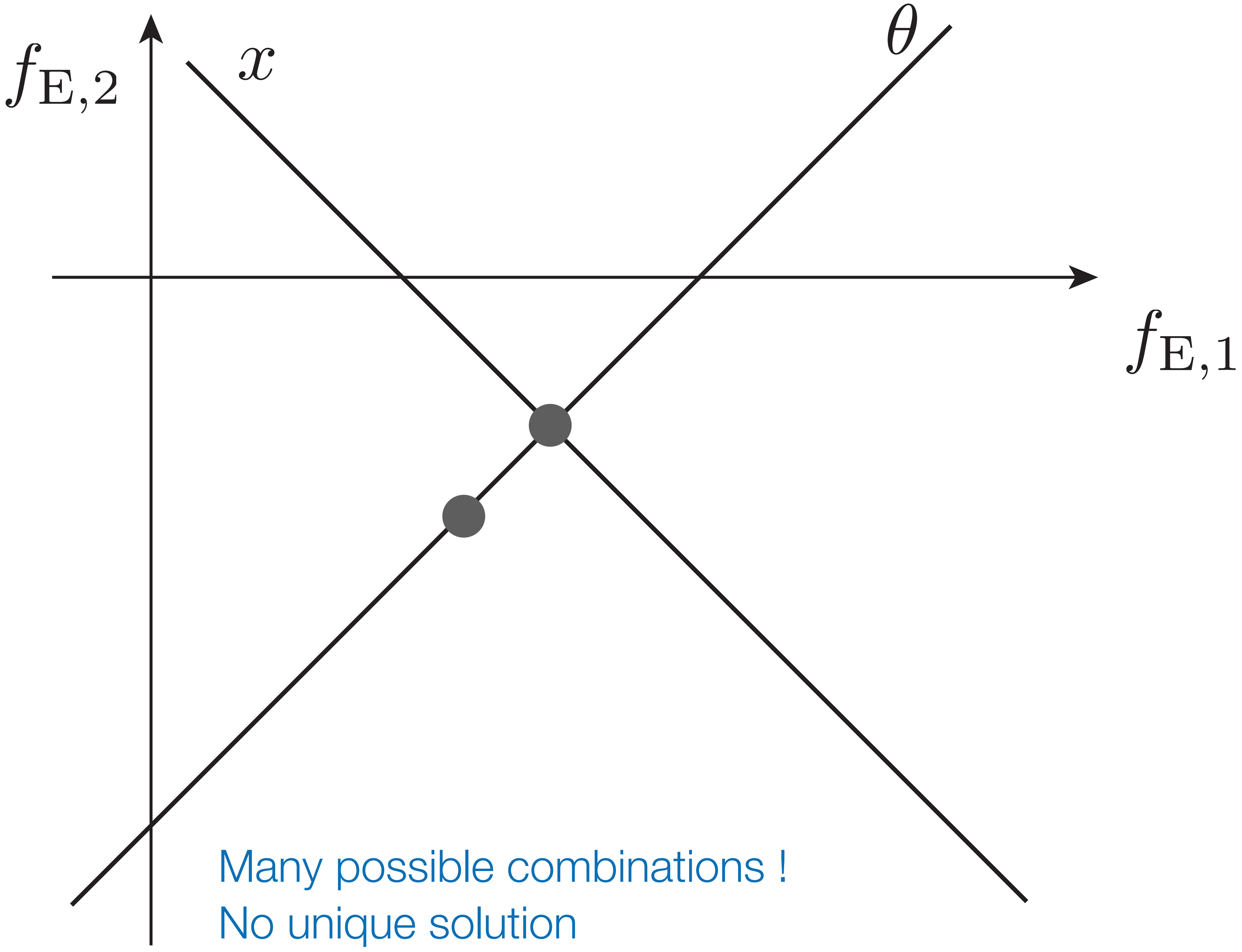
$$\frac{k_B}{\ell}x_{\max} = f_{E,2} + f_{E,1}$$

Nb. of LOADS = Nb. of responses

Problem is now properly closed

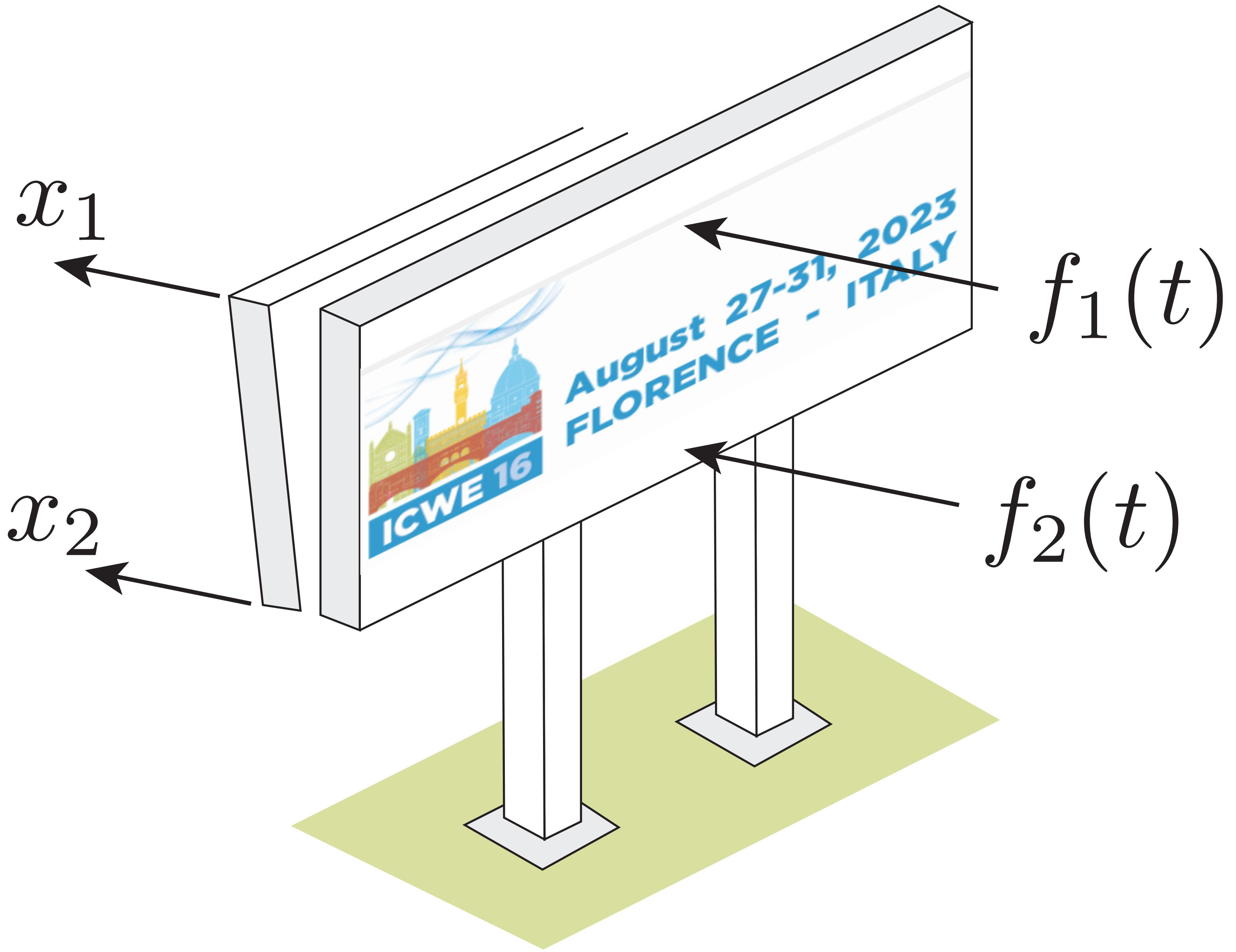
(but be careful again, this is an example)

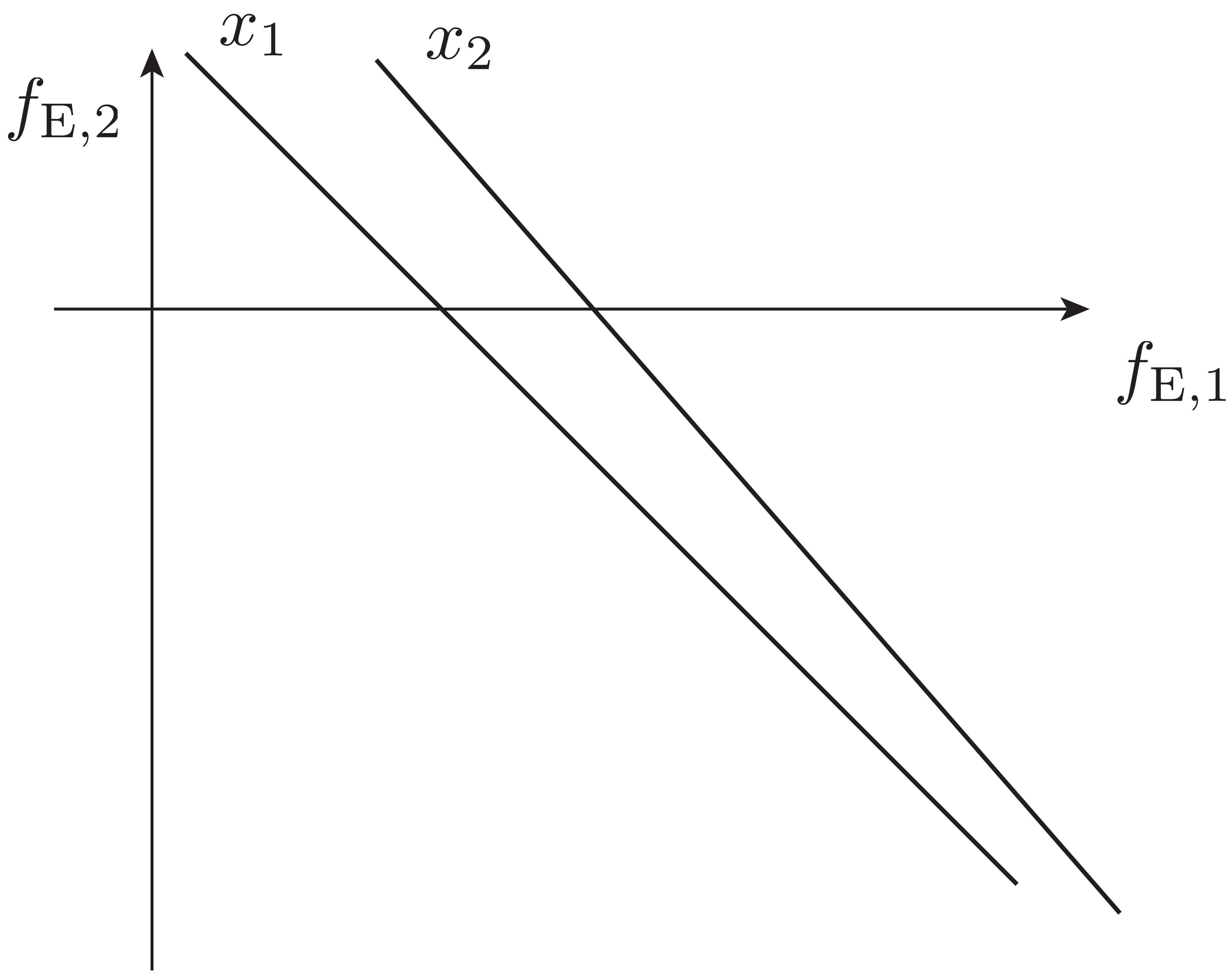




(1) 2-DOF Mass-spring oscillator - drag only

Same problem, modeled as a 2-DOF structure (but $x_2(t) = \frac{1}{2} x_1(t) \quad \forall t$)





What is an Equivalent Static Wind Load ?

Static : replace dynamic analysis by static analysis

Equivalent (to what?) : should reproduce the same maximum response

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}$$

$$\mathbf{z}(t) = \mathbf{A}\mathbf{x}(t) \qquad \mathbf{z}_{\max} = \max_t \mathbf{z}(t)$$

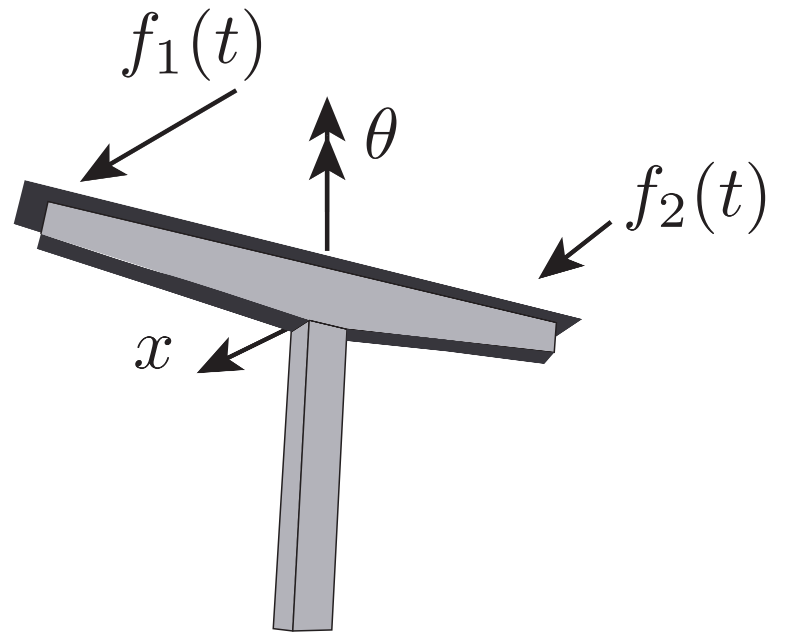
Find $\mathbf{f}_\mathrm{E}$ such that: $\mathbf{K}\mathbf{x}_\mathrm{E} = \mathbf{f}_\mathrm{E}$ and $\mathbf{A}\mathbf{x}_\mathrm{E} = \mathbf{z}_{\max}$

Is the problem well posed ? Is the solution unique ?

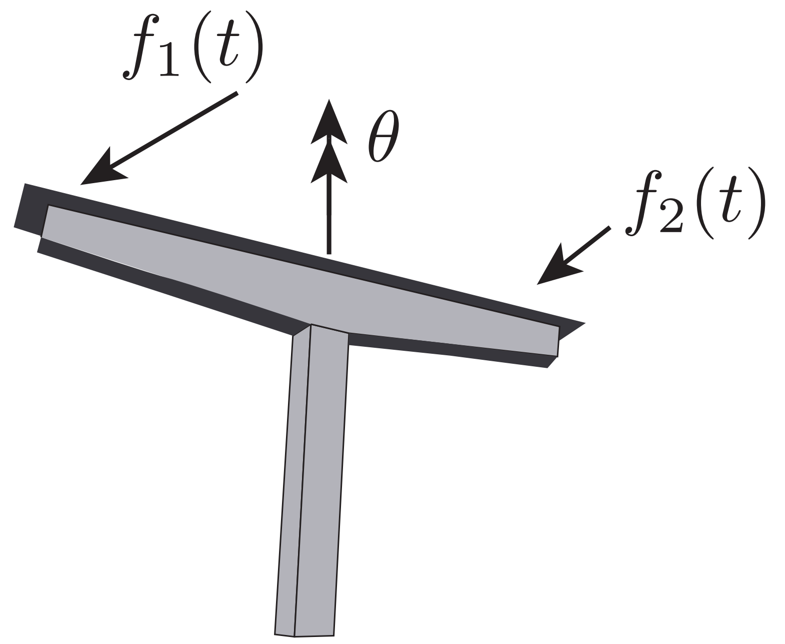
$$\mathbf{A}\mathbf{K}^{-1}\mathbf{f}_\mathrm{E} = \mathbf{z}_{\max}$$

Nb. of *LOADS* = Nb. of *RESPONSES* $\longleftrightarrow$ $\mathbf{A}\mathbf{K}^{-1}$ is square

Determined



Under-determined



Over-Determined

GRF & Covariance Proper Transformation (CPT)

$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}$

$\mathbf{z}(t) = \mathbf{A}\mathbf{x}(t) \qquad \mathbf{z}_{\max} = \max_t \mathbf{z}(t)$

Find $\mathbf{f}_{\mathrm{E}}$ such that: $\mathbf{K}\mathbf{x}_{\mathrm{E}} = \mathbf{f}_{\mathrm{E}}$ and $\mathbf{A}\mathbf{x}_{\mathrm{E}} = \mathbf{z}_{\max}$

Informs about loading only

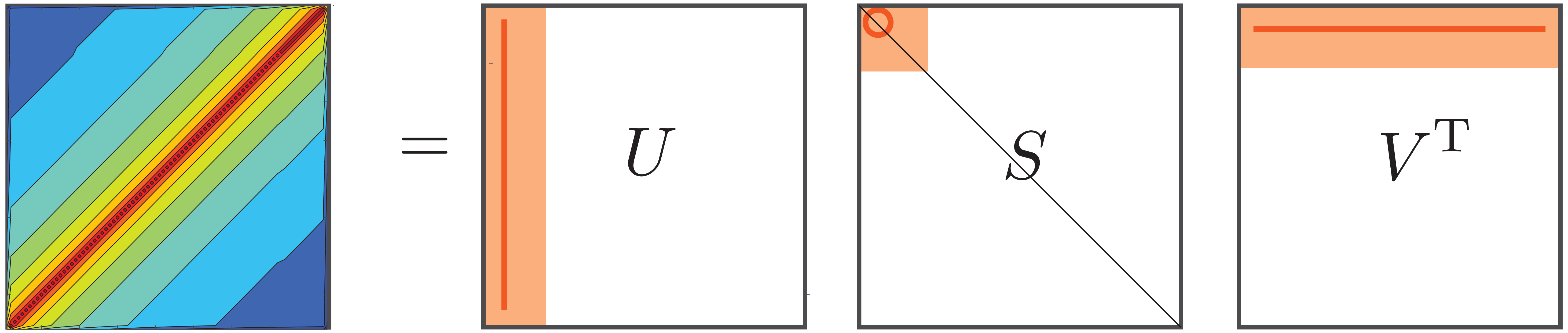
Average loading : $\bar{\mathbf{f}}$

Covariance of the loading : $\boldsymbol{\Sigma}_{\mathbf{f}} = \mathbb{E}\left[\mathbf{f}\,\mathbf{f}^T\right]$

$f_{\mathrm{E}}^{\mathrm{GRF}}$

$\mathbf{f}_{\mathrm{E}} \propto \bar{\mathbf{f}}$

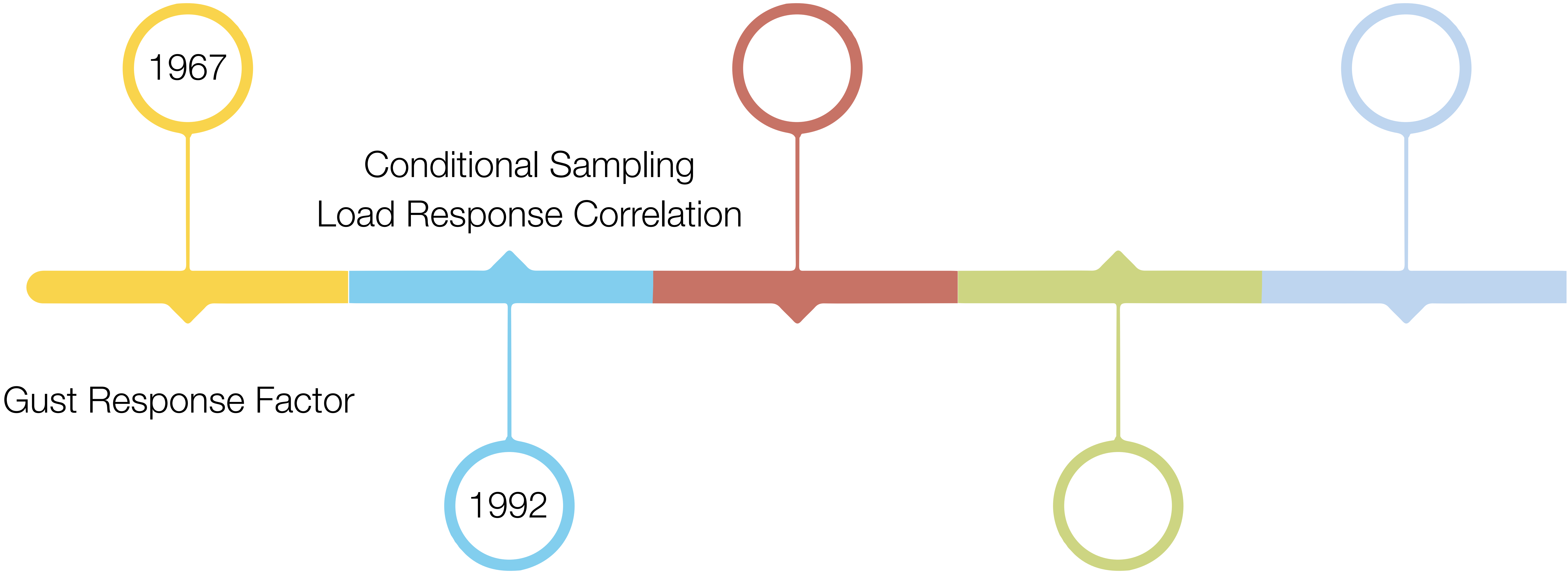
$f_{\mathrm{E}}^{\mathrm{CPT}}$



$\boldsymbol{\Sigma}_{\mathbf{f}}$ Eigen vectors Eigen values

Timeline

Davenport 1985; Holmes 1992;
Niemann @Bochum, 1992-95,
Holmes and Kasperski 1996;
Irwin 1998; Zhou et al. 2000



Davenport, 1967

The Load-Response Correlation method

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}$$

$$z(t) = \mathbf{a}^T\mathbf{x}(t) \qquad z_{\max} = \max_t z(t)$$

$$z(t) = \mathbf{b}^T\mathbf{f}(t)$$

Find $\mathbf{f}_\mathrm{E}$ such that: $\mathbf{K}\mathbf{x}_\mathrm{E} = \mathbf{f}_\mathrm{E}$ and $\mathbf{a}^T\mathbf{x}_\mathrm{E} = z_{\max}$

$$\mathbf{b}^T\mathbf{f}_\mathrm{E}(t) = z_{\max}$$

- Memoryless I/O relation
- No dynamics
- Gaussian response
- (Unique peak factor)

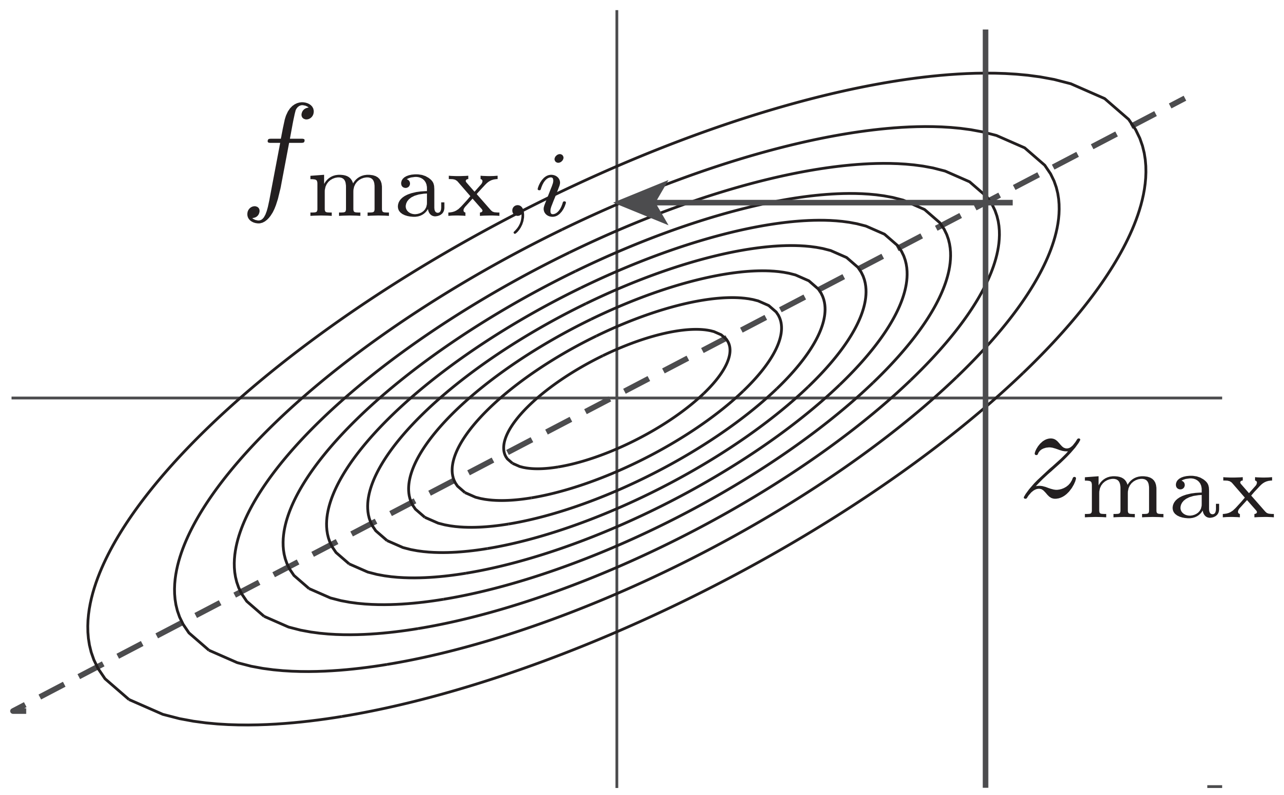
Assume Gaussian response : $$z_{\max} = g\sigma_z = g\frac{\sigma_z^2}{\sigma_z} = \frac{g}{\sigma_z}\sum_i\sum_j b_i b_j \mathrm{cov}_{f,ij}$$

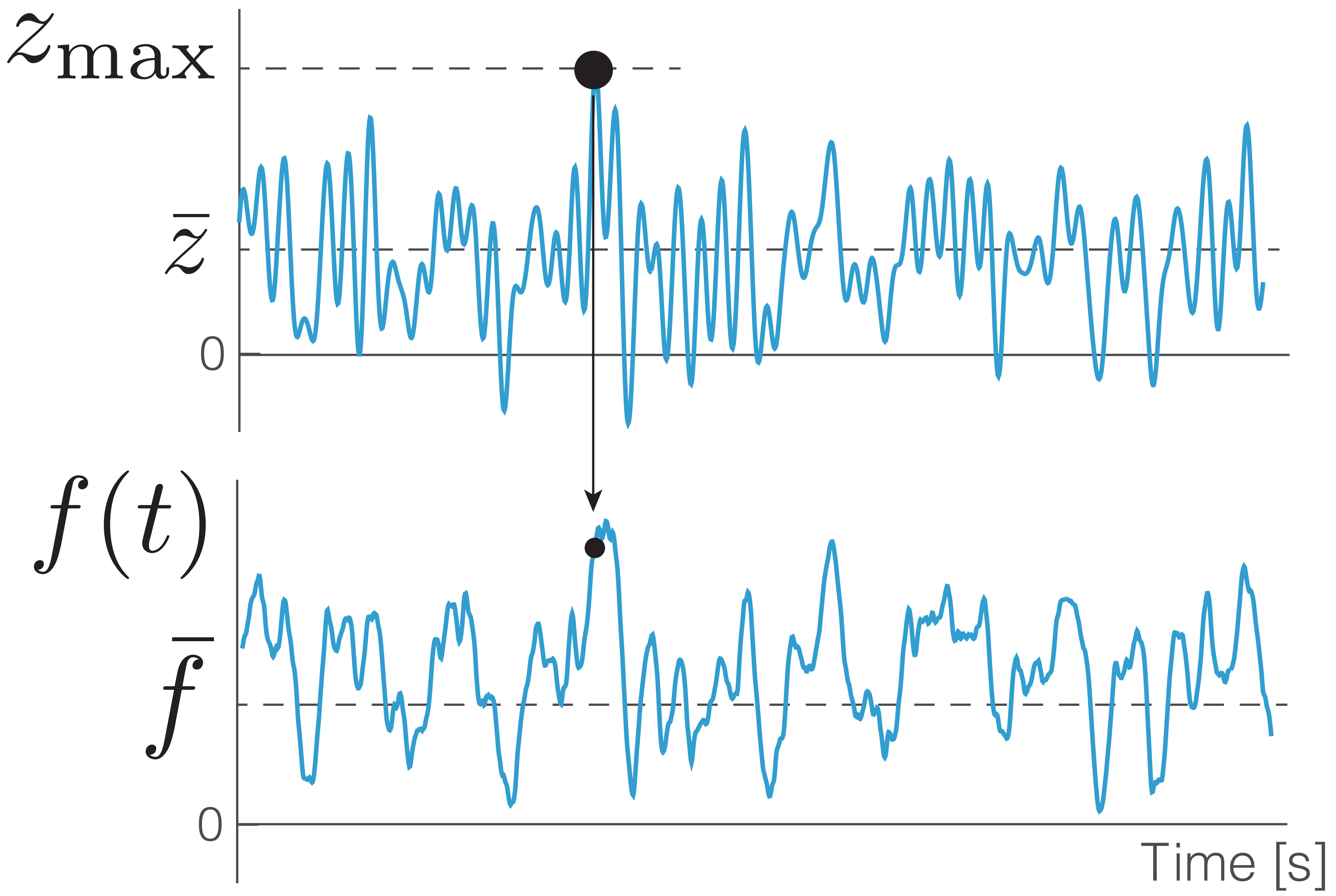
$$= \frac{g}{\sigma_z}\sum_i b_i \sum_j b_j \mathrm{cov}_{f,ij} = g\sum_i b_i \rho_{zf,i}\sigma_{f,i}$$

Assume same peak factor : $$f_{E,i}^{\mathrm{LRC}} = \rho_{zf,i} f_{\max,i}$$

The Load-Response Correlation method

$$f_{E,i}^{\mathrm{LRC}} = \rho_{zf,i} f_{\max,i}$$





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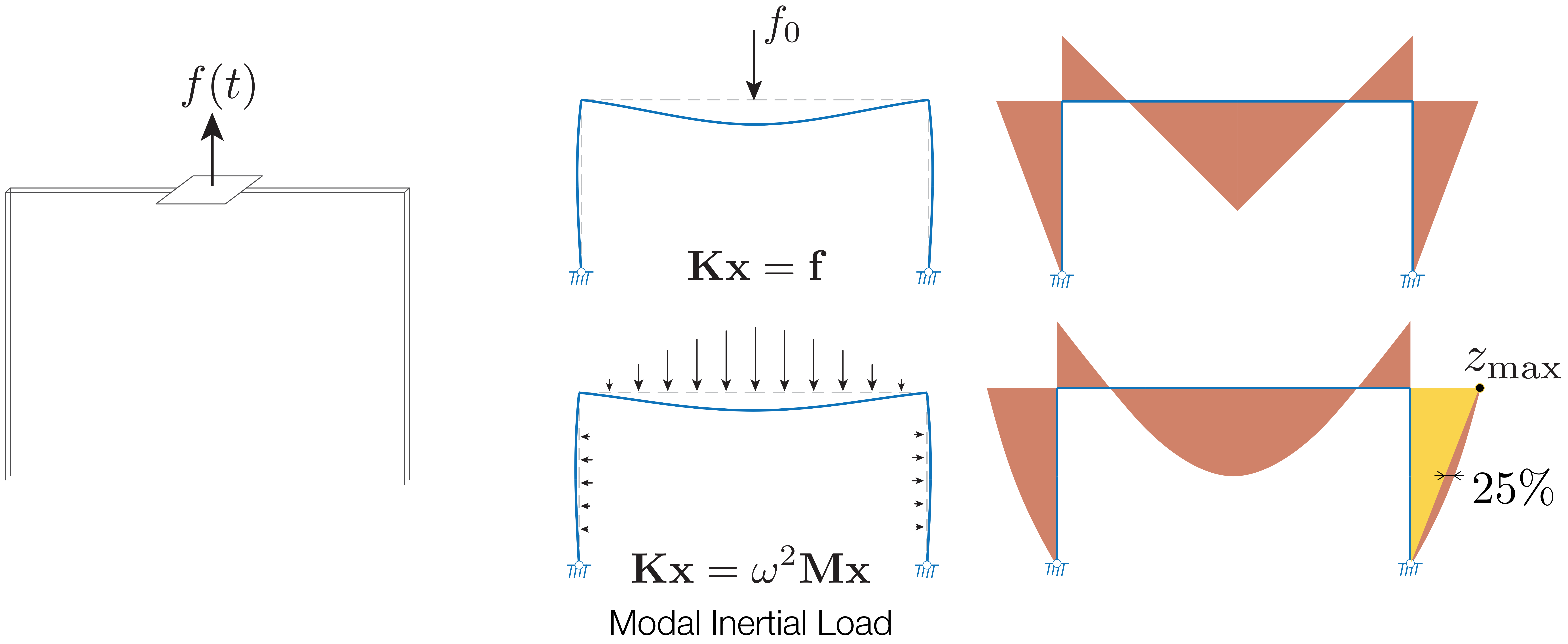
- Memoryless I/O relation
- No dynamics
- Gaussian response
- (Unique peak factor)

+

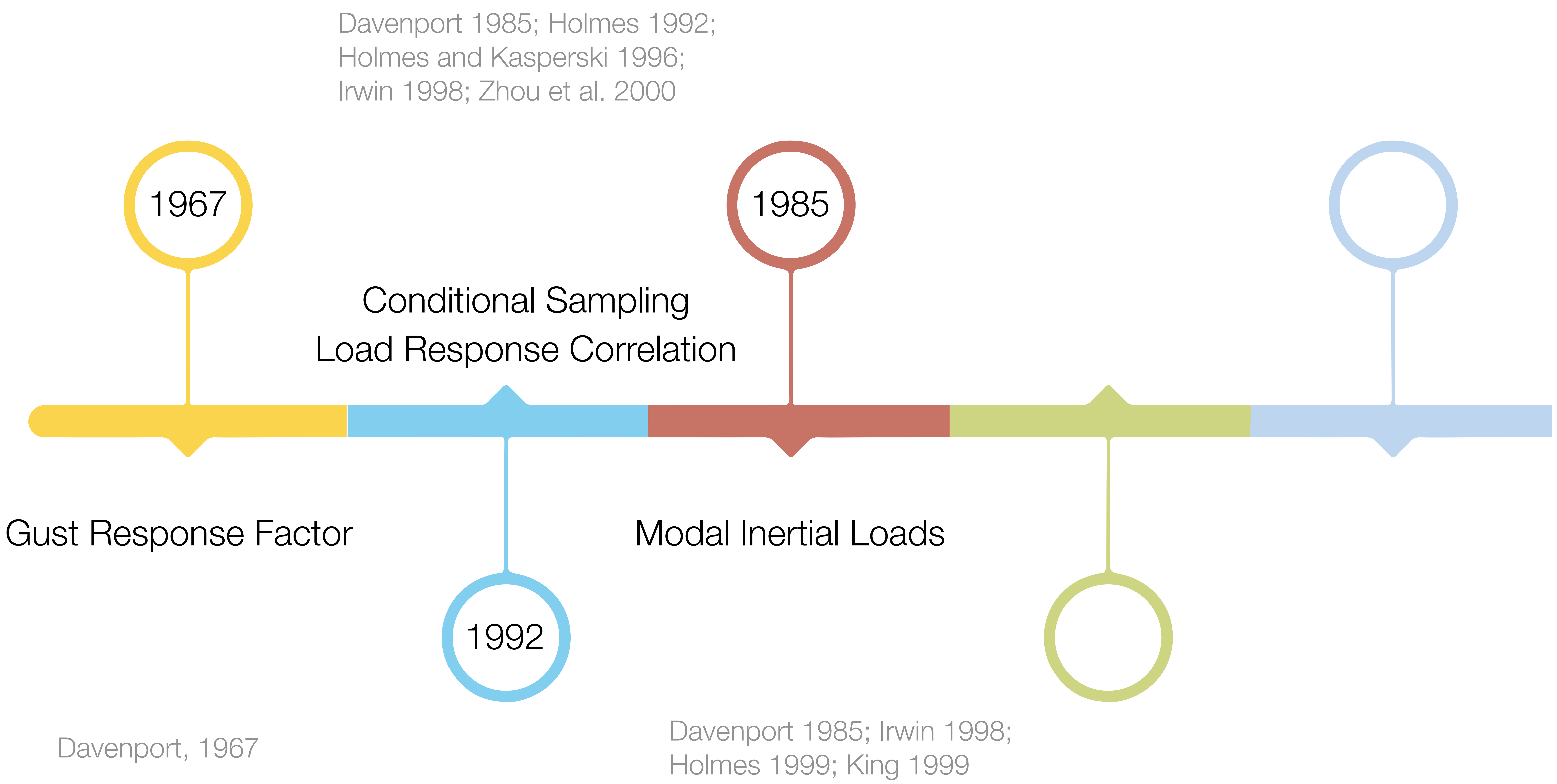
- Simple interpretation : most probable load
- Link with cond. sampling
- No overshooting of enveloppe (iif Gaussian)

The Load-Response Correlation method

The Load-Response Correlation method and the Conditional Sampling Technique have a drawback : equivalent loads are applied where pressures are measured



Timeline


Davenport 1985; Holmes 1992;
Holmes and Kasperski 1996;
Irwin 1998; Zhou et al. 2000
1967
1985
Conditional Sampling
Load Response Correlation
Gust Response Factor
Modal Inertial Loads
1992
Davenport, 1967
Davenport 1985; Irwin 1998;
Holmes 1999; King 1999

Modal Inertial Loads

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}$$

$$z(t) = \mathbf{a}^T \mathbf{x}(t) \simeq \mathbf{a}^T q(t) \boldsymbol{\phi}_i \qquad z_{\max} = \max_t z(t)$$

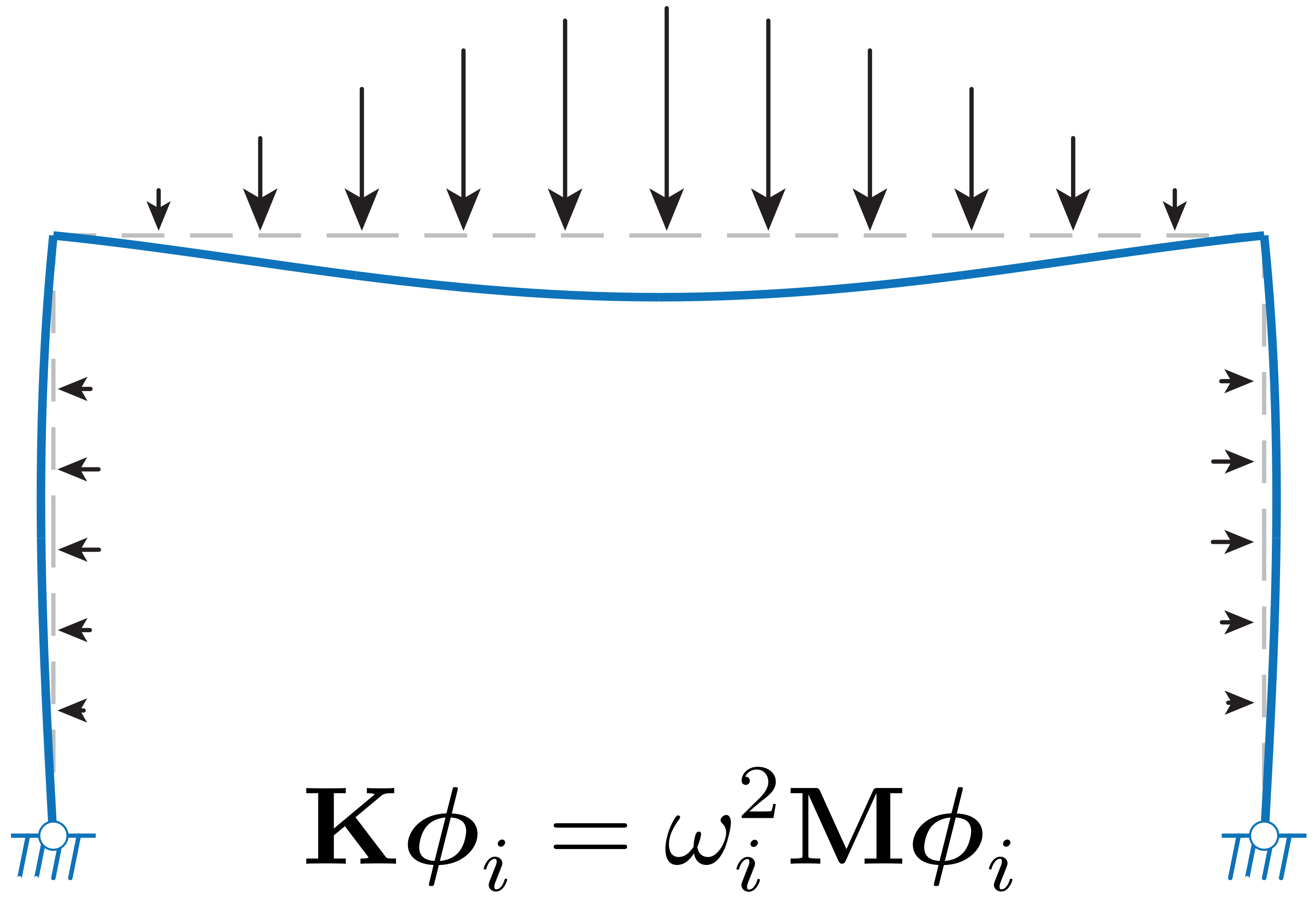
Find $\mathbf{f}_{\mathrm{E}}$ such that: $\mathbf{K}\mathbf{x}_{\mathrm{E}} = \mathbf{f}_{\mathrm{E}}$ and $\mathbf{a}^T \mathbf{x}_{\mathrm{E}} = z_{\max}$

$\sim \boldsymbol{\phi}_i$

$\mathbf{f}_E^{\mathrm{MIL}} = \mathbf{M}\boldsymbol{\phi}_i$

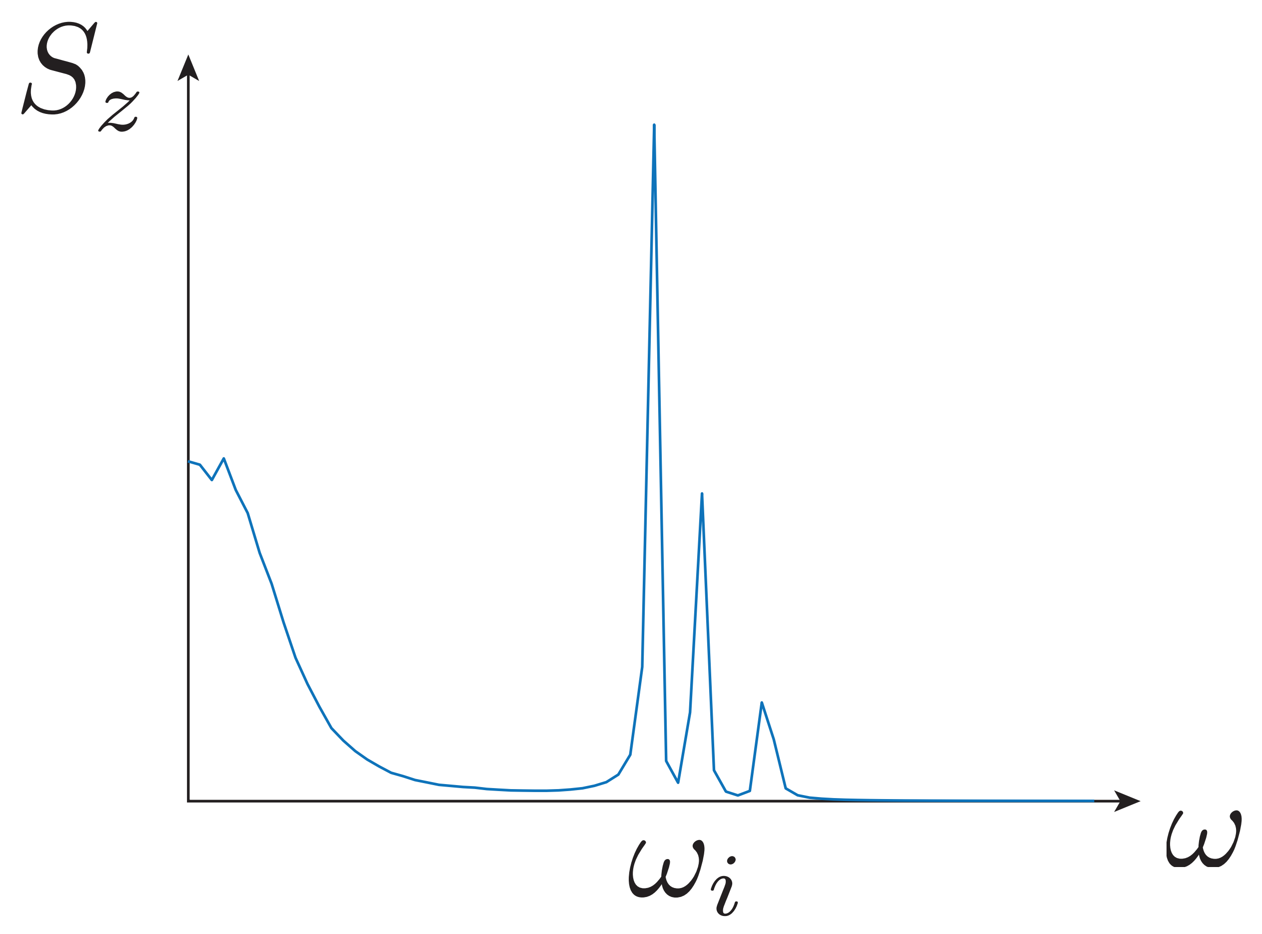
- Deformation = Mode shape
- Resonant Response
- Extension to multiple modes

Equivalent loads are applied where the mass is



Load Response Correlation vs. Modal Inertial Loads

	LRC	MIL
Response	**background** (wrong otherwise)	**resonant** (wrong otherwise)
Load pattern	Most probable load (conditional, Gaussianity)	Inertial loads (conditional, Gaussianity)
Simple physical meaning	✓	✓



Timeline

1967

Gust Response Factor

Davenport, 1967

1992

Conditional Sampling
Load Response Correlation

Davenport 1985; Holmes 1992;
Holmes and Kasperski 1996;
Irwin 1998; Zhou et al. 2000

1985

Modal Inertial Loads

Davenport 1985; Irwin 1998;
Holmes 1999; King 1999

1998

Background/Resonant
Conditional Expected Load

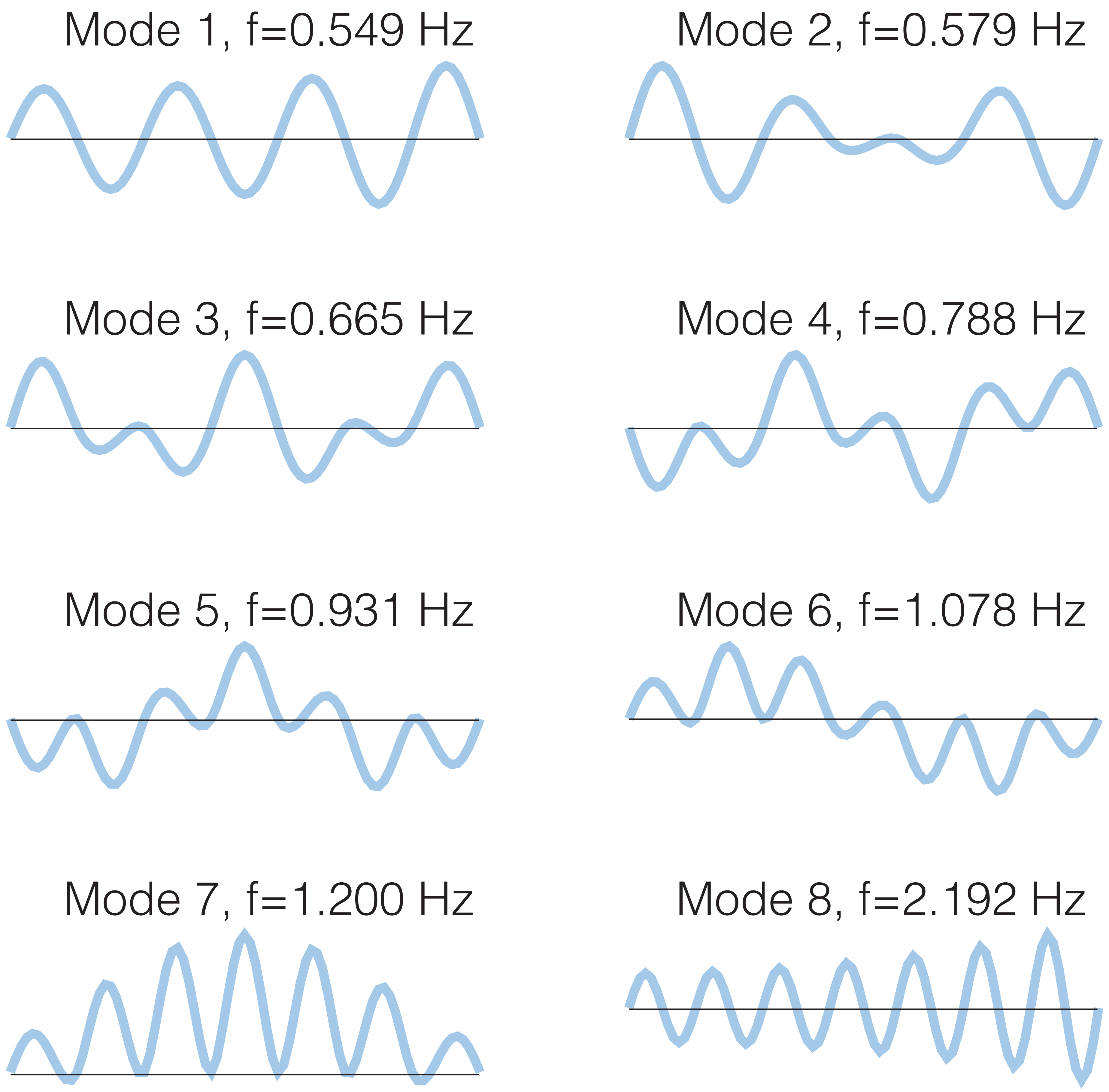
Irwin 1998; Holmes 1999;
King 1999; Chen & Kareem (2001);
Blaise and Denoël (2012-2013)

Background/Resonant combinations

$$\mathbf{f}_{\mathrm{E}} = W_b \mathbf{f}_{\mathrm{E}}^{\mathrm{LRC}} + \sum_i W_{r,i} \mathbf{f}_{\mathrm{E},i}^{\mathrm{MIL}} \qquad W_b = \frac{\sigma_{z,b}}{\sigma_z} \quad ; \quad W_{r,i} = \sum_j \rho_{q,ij} \frac{\sigma_{z,r_j}}{\sigma_z}$$

- Weighted combination of LRC and MIL methods
- Degenerates into LRC and MIL
- In original formulation: nodal background & modal resonant
- Different variants :
  - without modal correlation (Holmes, 1999)
  - with modal correlation (Chen & Kareem, 2001)
  - including non-proportional damping (Blaise & Denoël, 2013)
  - …

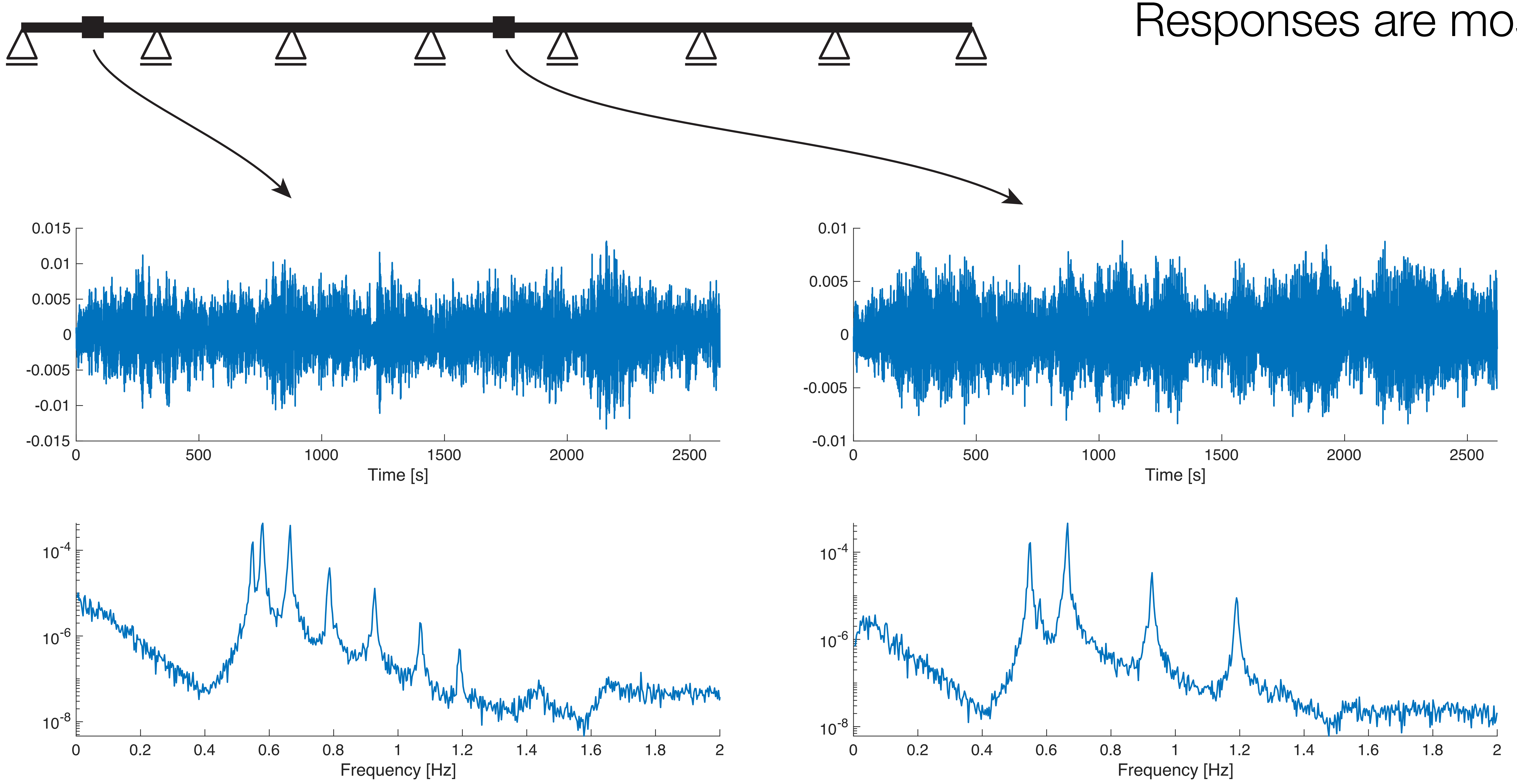
Illustration



- 7-span viaduct (6@300m + 1@305m)
- Subject to turbulent wind :
  - Drag only
  - Spectrum : ENV1991-1.4, Annex B
  - Linearized loading (Gaussian)
- Model :
  - 84 Euler-Bernoulli finite elements
  - Mass = 10 to/m, $EI=10^{13}\ Nm^2$
- Analysis :
  - Time domain simulation
  - DT=0.04s, 65536 steps, T=2621 s

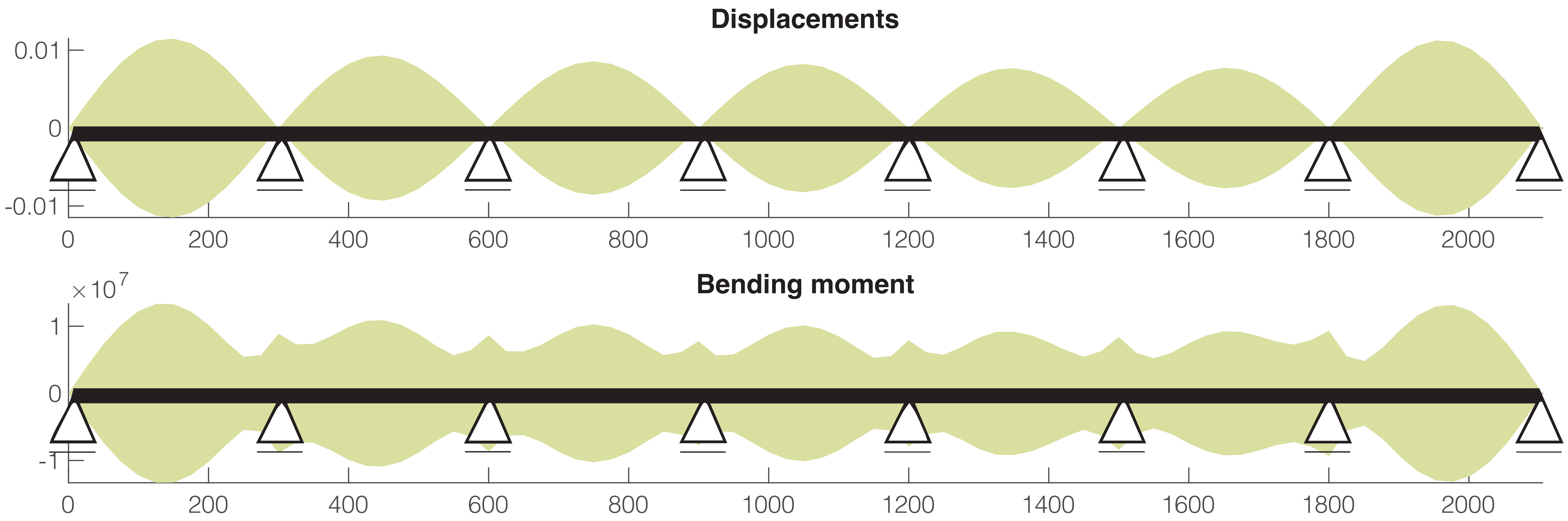
Illustration - overview of dynamic behavior

Responses are mostly resonant



$$\mathbf{z} = \begin{pmatrix} x_1 \\ \vdots \\ x_n \\ M_1 \\ \vdots \\ M_n \end{pmatrix}$$

Illustration



$$\mathbf{z} = \begin{pmatrix} x_1 \\ \vdots \\ x_n \\ M_1 \\ \vdots \\ M_n \end{pmatrix}$$

Envelope = (Zero-mean) + 3.5 · (Standard deviation)

Next : (GRF), CPT, LRC, MIL, COMB

Illustration : Covariance Proper Decomposition (CPT)

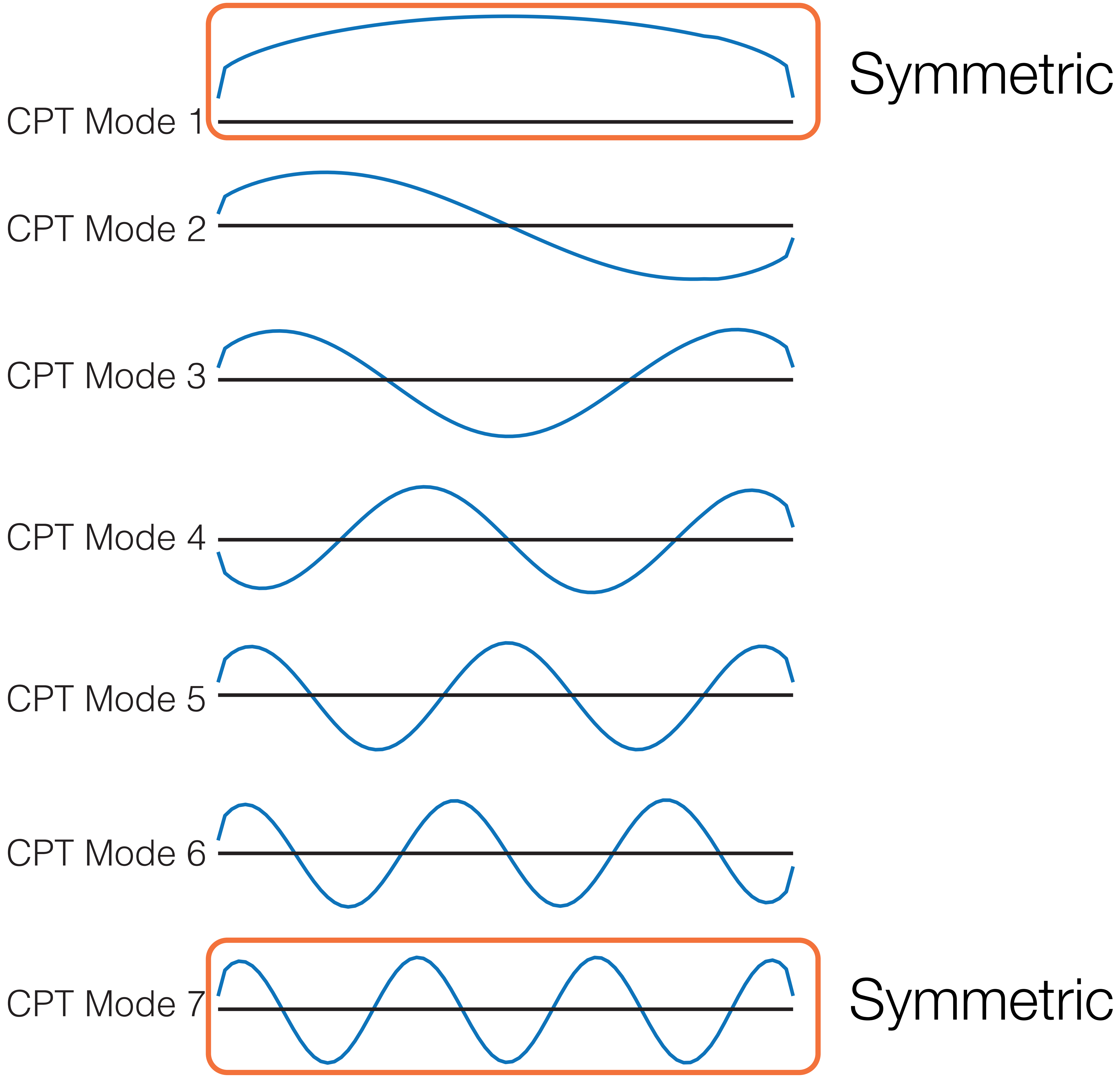


Illustration : Covariance Proper Decomposition (CPT)

Significant overshooting !

Now Ok.

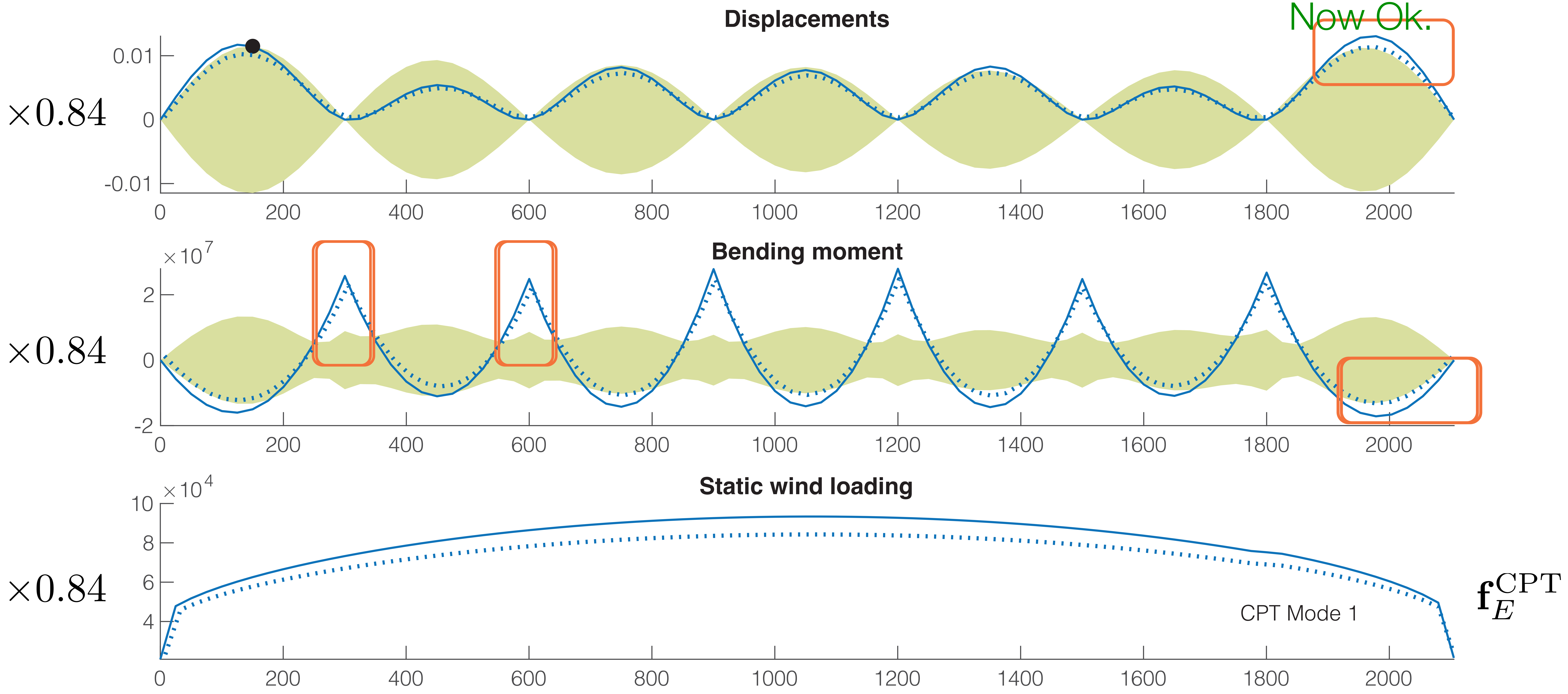
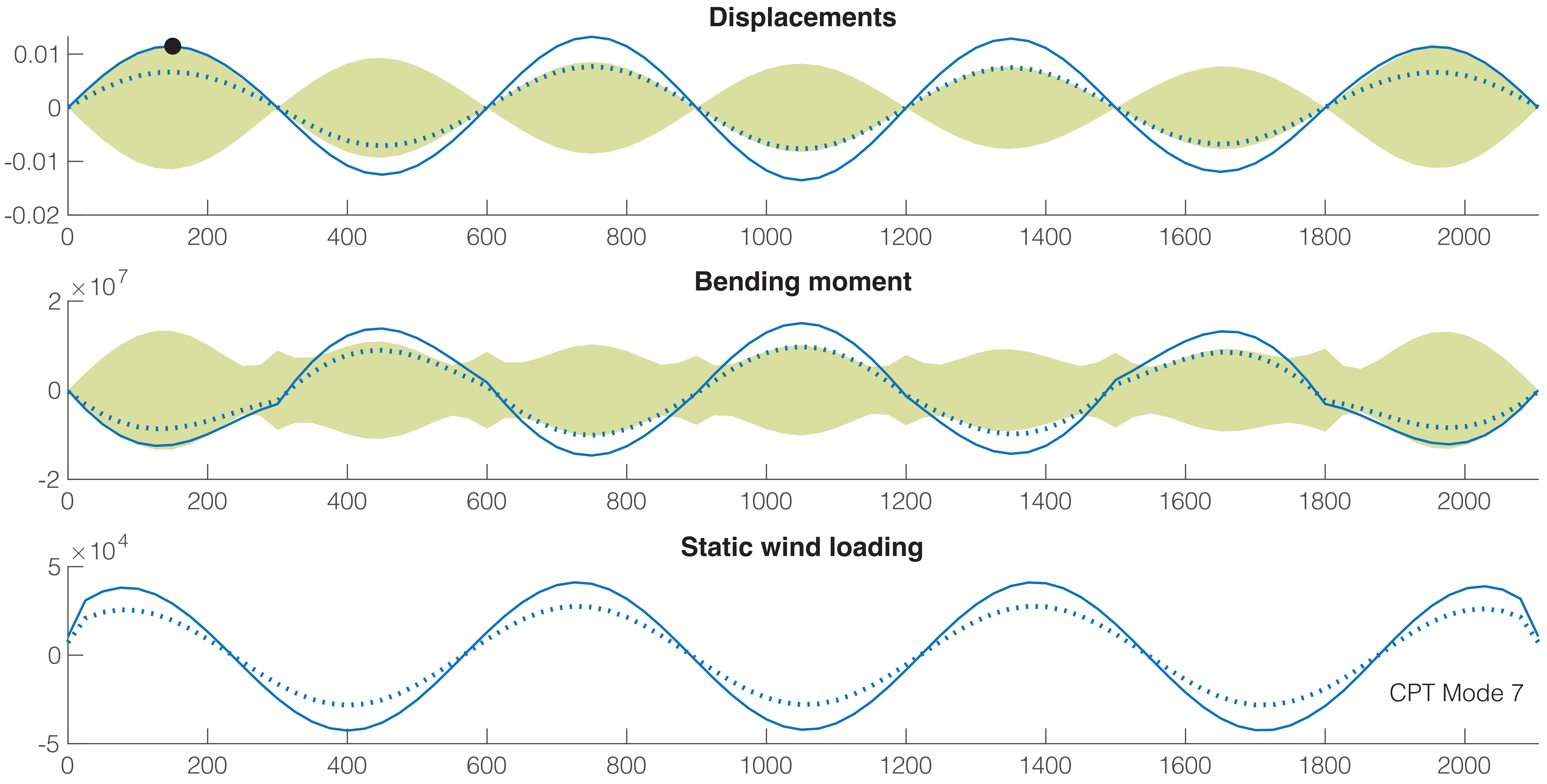
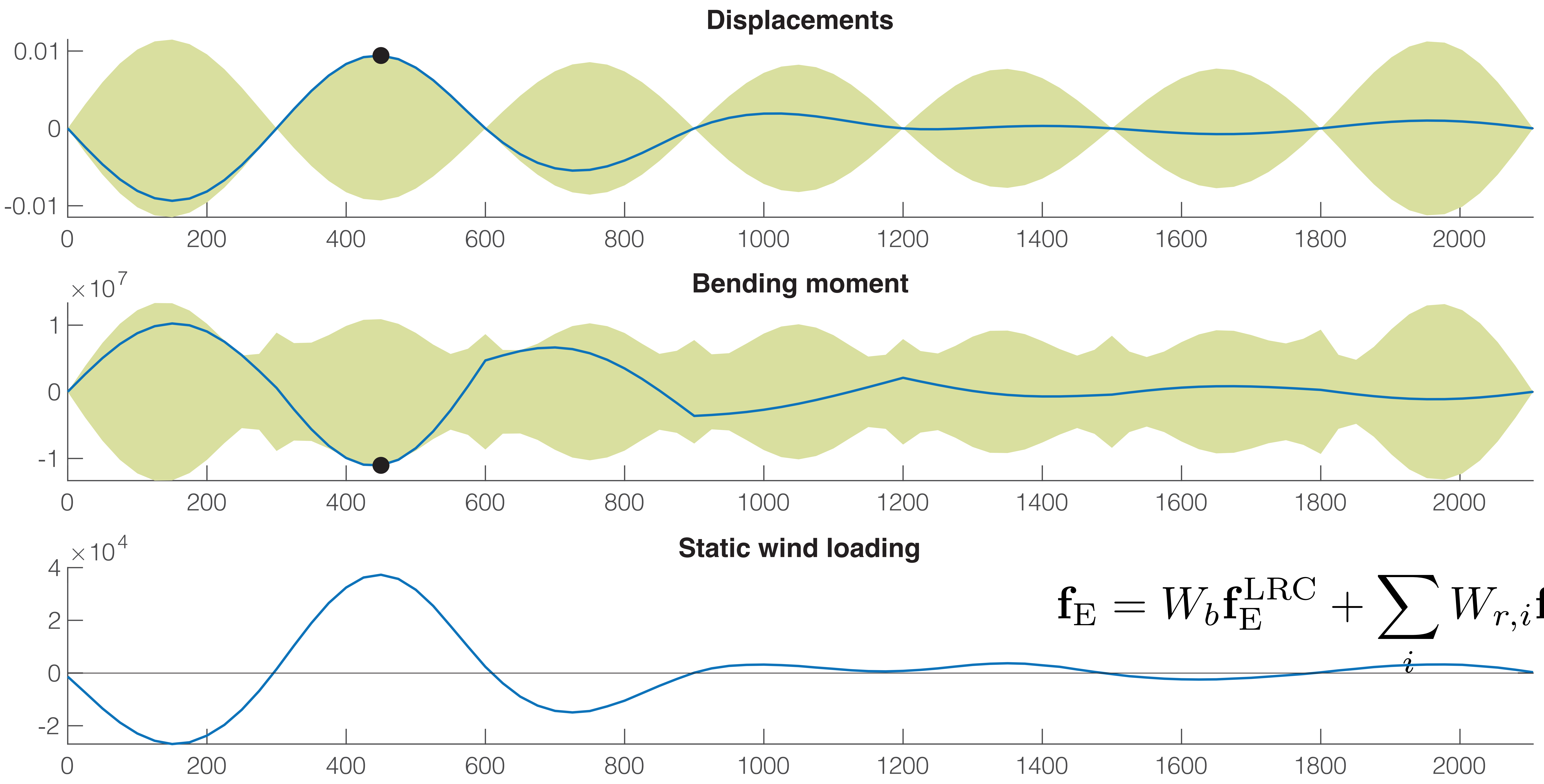


Illustration : Covariance Proper Decomposition (CPT)



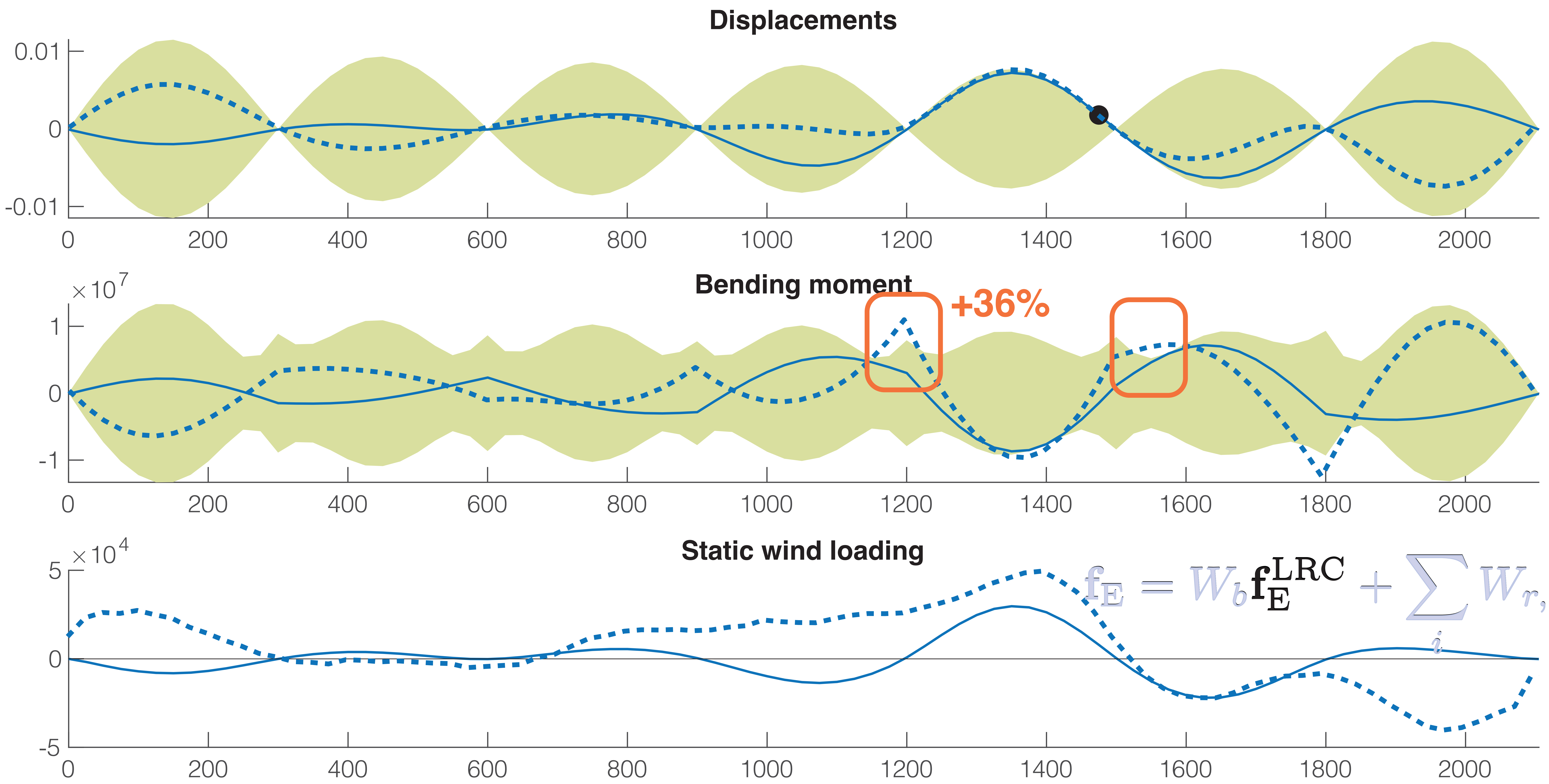
$\mathbf{f}_E^{\mathrm{CPT}}$

Illustration - Background/Resonant combinations



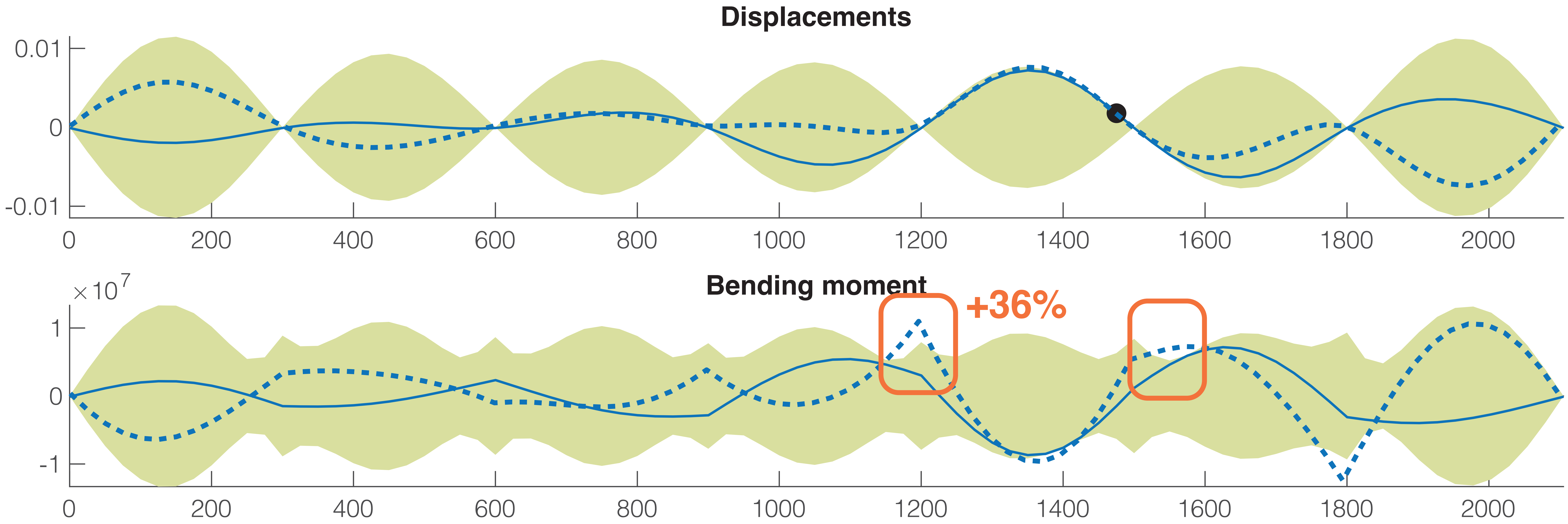
$$\mathbf{f}_{\mathrm{E}} = W_b \mathbf{f}_{\mathrm{E}}^{\mathrm{LRC}} + \sum_i W_{r,i} \mathbf{f}_{\mathrm{E},i}^{\mathrm{MIL}}$$

Illustration - Background/Resonant combinations



$$\mathbf{f}_{\mathrm{E}} = W_b \mathbf{f}_{\mathrm{E}}^{\mathrm{LRC}} + \sum_i W_{r,i} \mathbf{f}_{\mathrm{E},i}^{\mathrm{MIL}}$$

Illustration - Background/Resonant combinations



LRC overshoots other responses than the one that is reconstructed

Solution : scale down the ESWL to avoid ***overestimation***

Provisional conclusion

	LRC	MIL	COMBINED
Response	**background** (wrong otherwise)	**resonant** (wrong otherwise)	**both**
Load pattern	Most probable load (conditional, Gaussianity)	Inertial loads (conditional, Gaussianity)	Conditional
Simple physical meaning	✓	✓	✓
No overshooting	✗	✗	✓

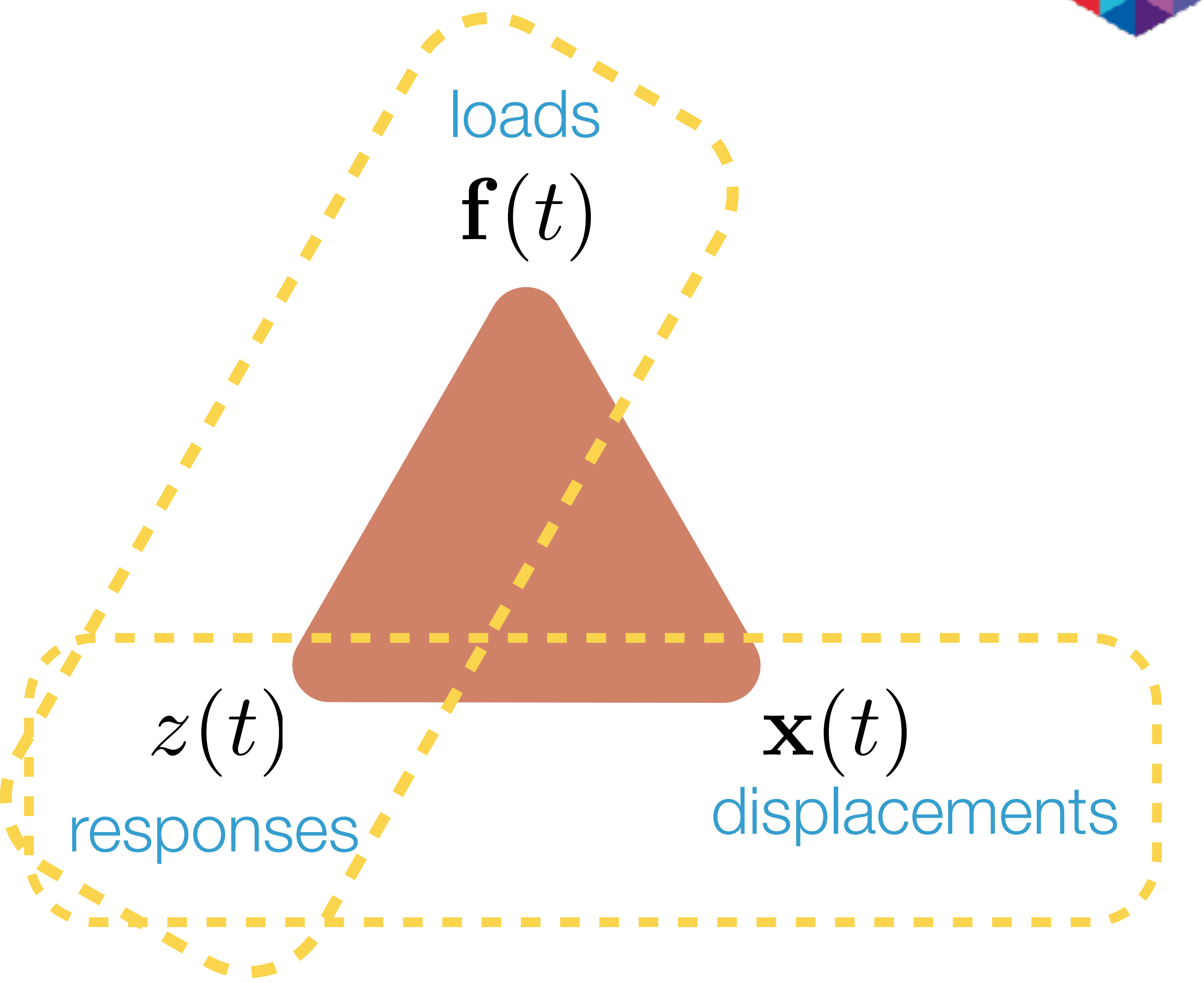
Possibility to extend

Displacement-Response Correlation

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}$$

$$z(t) = \mathbf{a}^T \mathbf{x}(t) \qquad z_{\max} = \max_t z(t)$$

Find $\mathbf{f}_{\mathrm{E}}$ such that: $\mathbf{K}\mathbf{x}_{\mathrm{E}} = \mathbf{f}_{\mathrm{E}}$ and $\mathbf{a}^T \mathbf{x}_{\mathrm{E}} = z_{\max}$



- in the LRC:
  - use of correlation between loads and responses
  - loads are proportional to structural displacements (static only)
- in the MIL :
  - modal contributions to the response are most probable inertial loads
  - loads are proportional to structural displacements, i.e. modes shapes (resonant only)

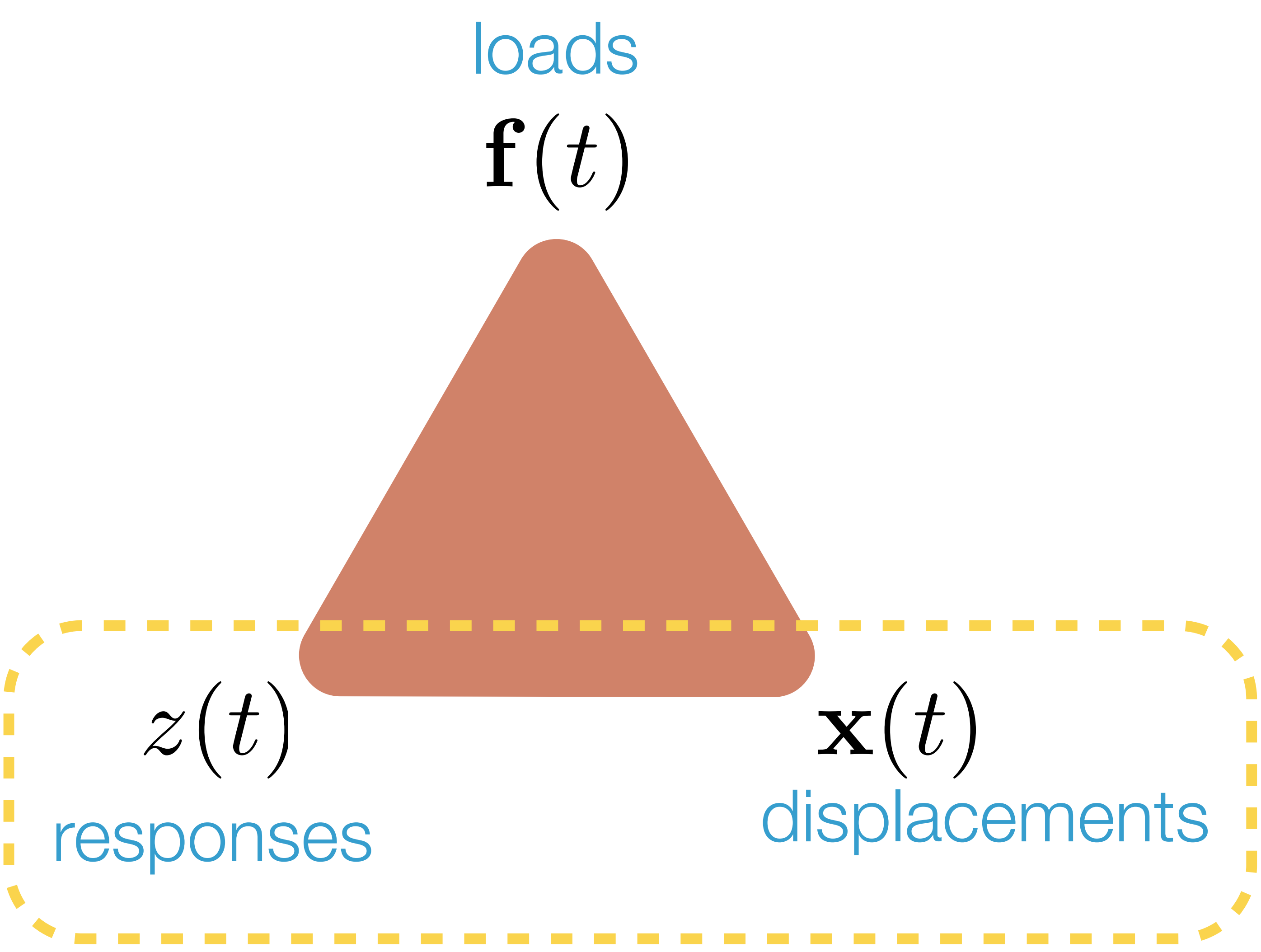
Equivalent wind loads: obtained from the most probable deformation of the structure when the response reaches its maximum value

Displacement-Response Correlation

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}$$

$$z(t) = \mathbf{a}^T \mathbf{x}(t) \qquad z_{\max} = \max_t z(t)$$

Find $\mathbf{f}_{\mathrm{E}}$ such that: $\mathbf{K}\mathbf{x}_{\mathrm{E}} = \mathbf{f}_{\mathrm{E}}$ and $\mathbf{a}^T \mathbf{x}_{\mathrm{E}} = z_{\max}$



- 1. Solve equation of motion: compute $\mathbf{x}(t)$ from measured dynamic loads $\mathbf{f}(t)$
- 2. Compute response $z(t)$ from displacements $\mathbf{x}(t)$ (NB: possibly nonlinear)
- 3. Build a joint probabilistic model for the response and displacements (joint Gaussian if applicable, this is now a choice, not an assumption)
- 4. Find the most probable (or average) displacement field $\mathbf{x}_{\mathrm{E}}$, conditioned upon the max. response
- 5. Determine the corresponding load distribution

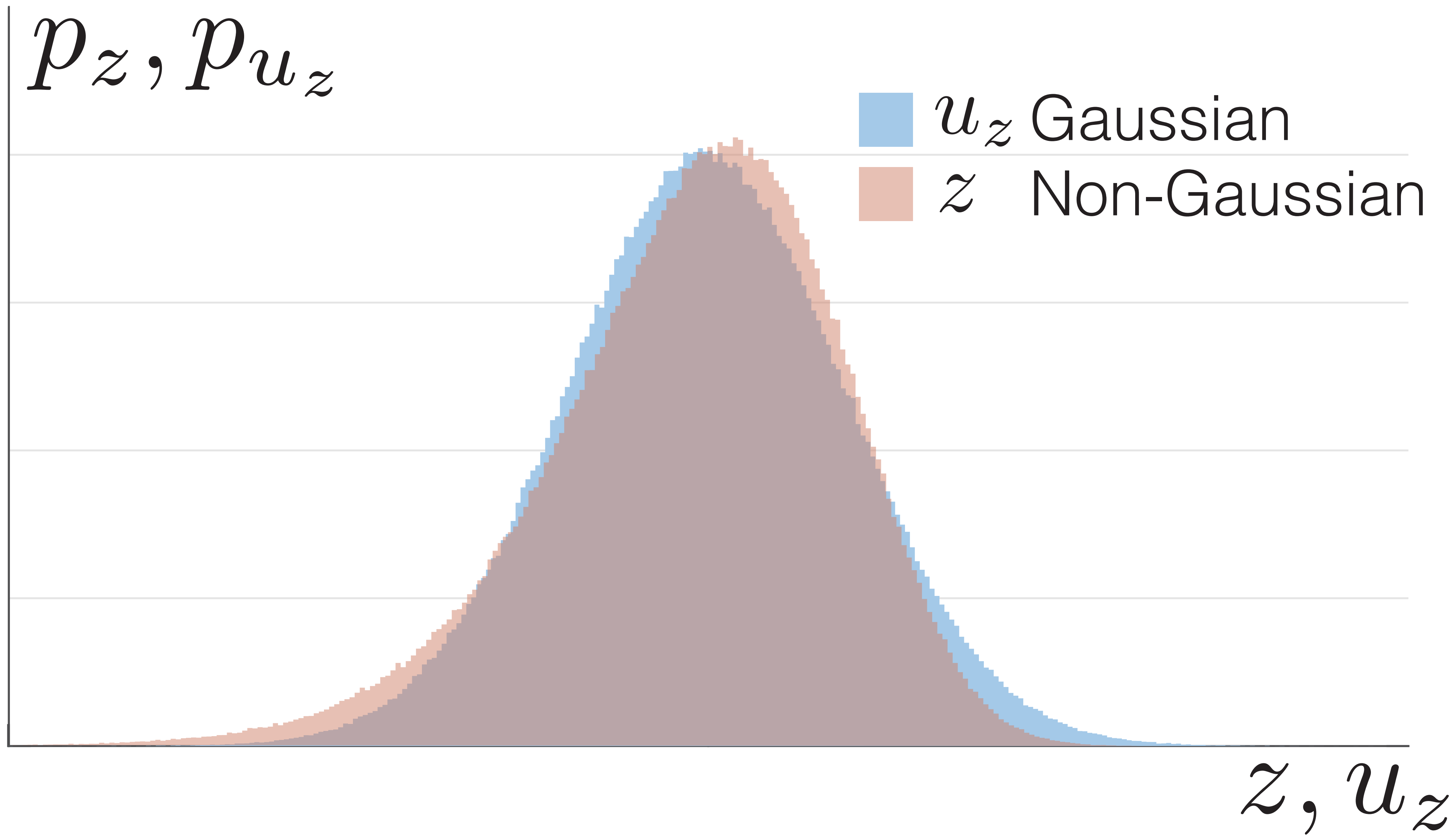
Equivalent wind loads: obtained from the most probable deformation of the structure when the response reaches its maximum value

The bicubic translation model

z Response

1	2	3	4
μ_z	σ_z	$\gamma_{3,z}$	$\gamma_{4,z}$

$$z = \frac{\alpha_z}{b_z}\left(\frac{u_z^3}{3} + a_z u_z^2 + (b_z - 1)\, u_z - a_z\right)$$



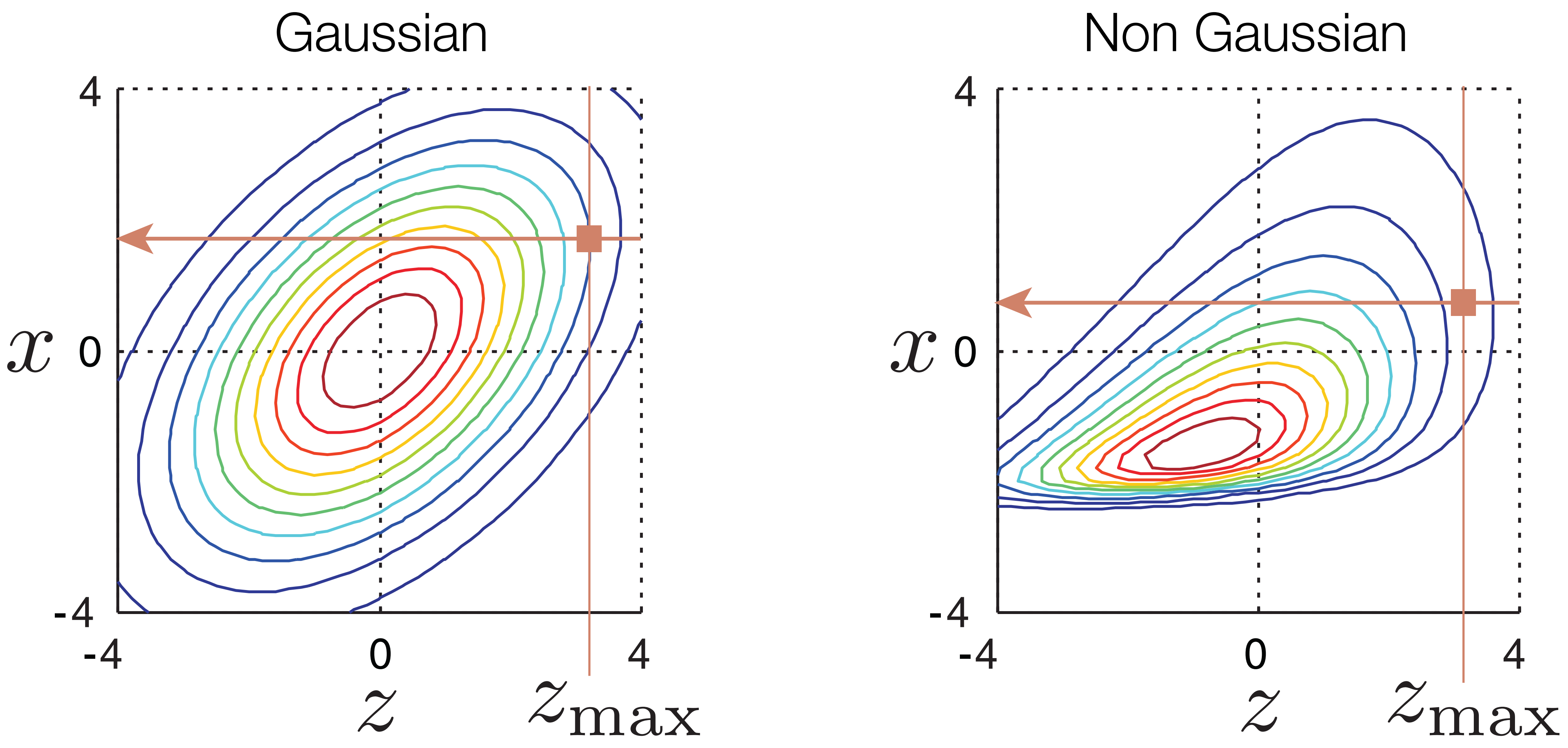
The bicubic translation model

z Response / x Displacement

x \ z	0	1	2	3	4
0		μ_z	σ_z	$\gamma_{3,z}$	$\gamma_{4,z}$
1	μ_x	ρ_{xz}			
2	σ_x				
3	$\gamma_{3,x}$				
4	$\gamma_{4,x}$				

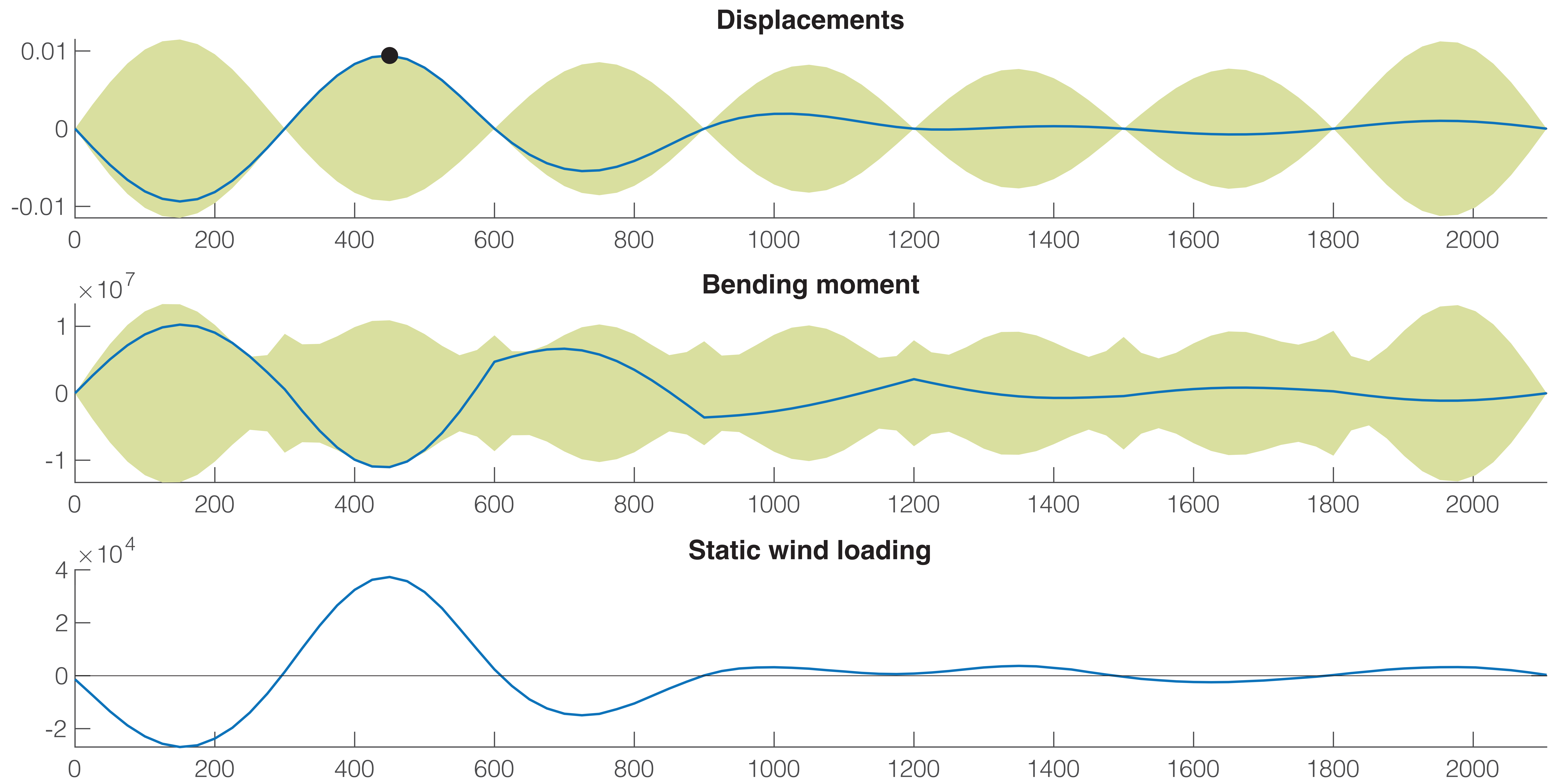
$$z = \frac{\alpha_z}{b_z}\left(\frac{u_z^3}{3} + a_z u_z^2 + (b_z - 1)\, u_z - a_z\right)$$

$$x = \frac{\alpha_x}{b_x}\left(\frac{u_x^3}{3} + a_x u_x^2 + (b_x - 1)\, u_x - a_x\right)$$

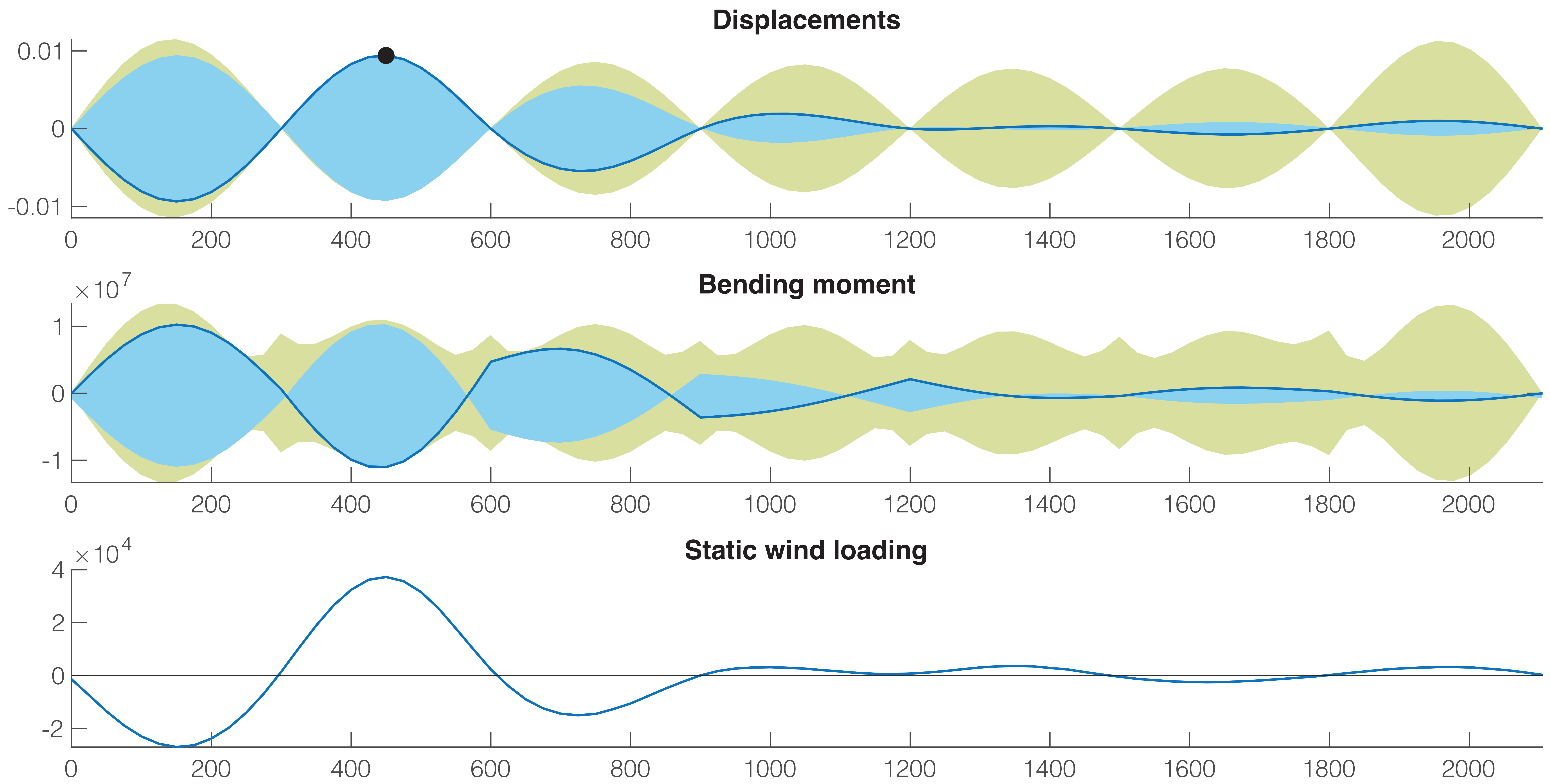


Part II : Envelope Reconstruction Problem

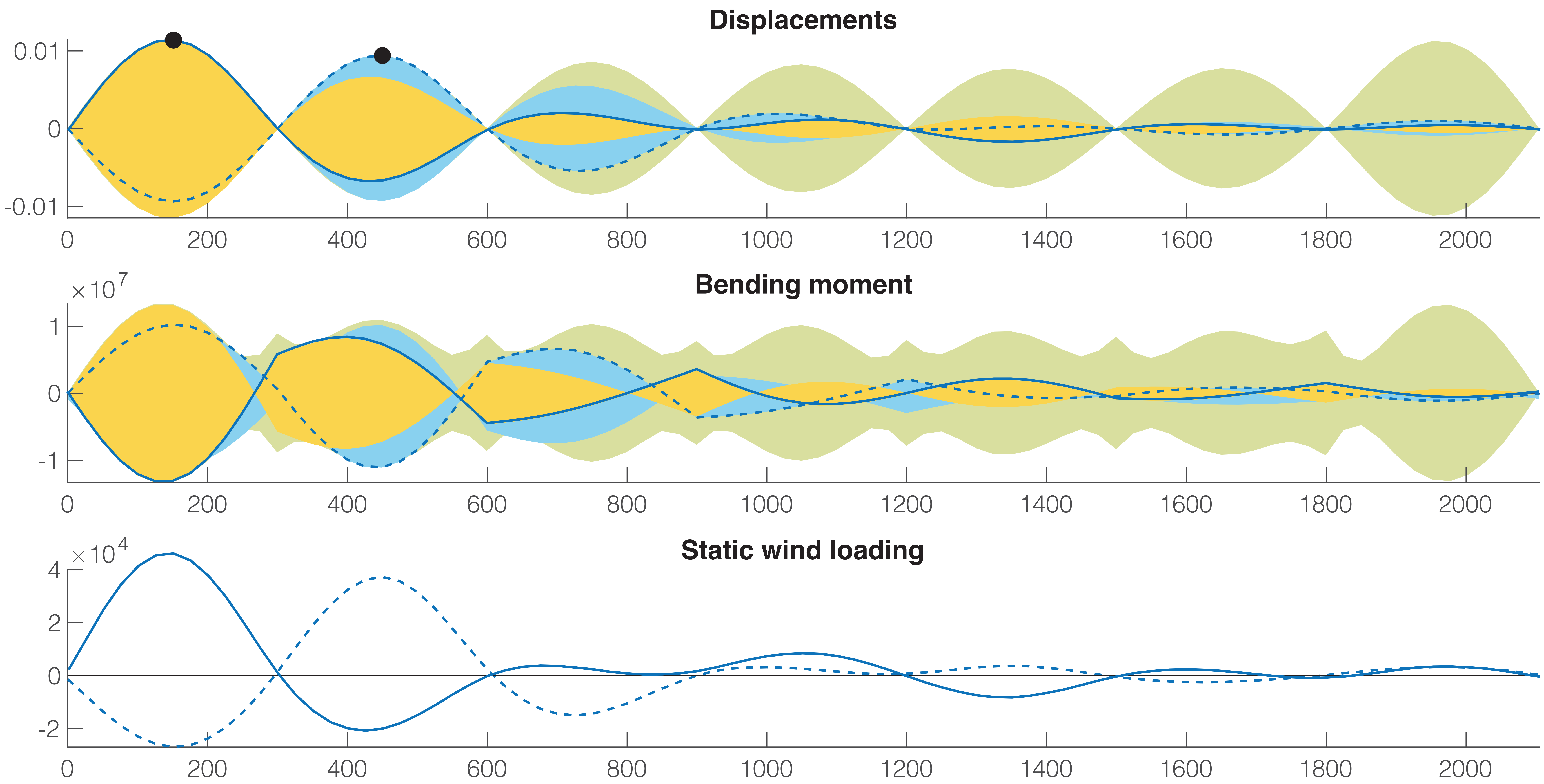
The Envelope Reconstruction Problem



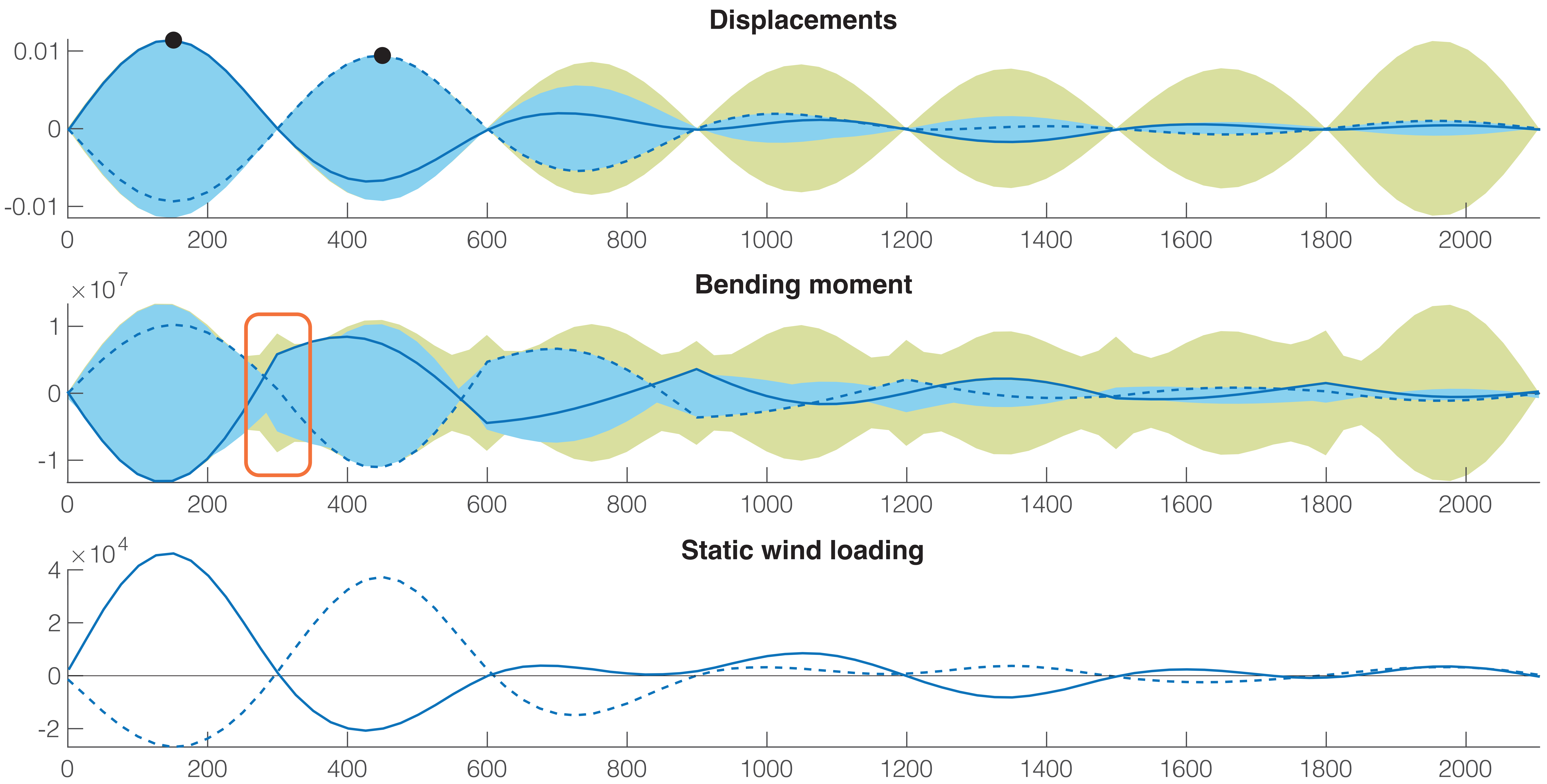
The Envelope Reconstruction Problem



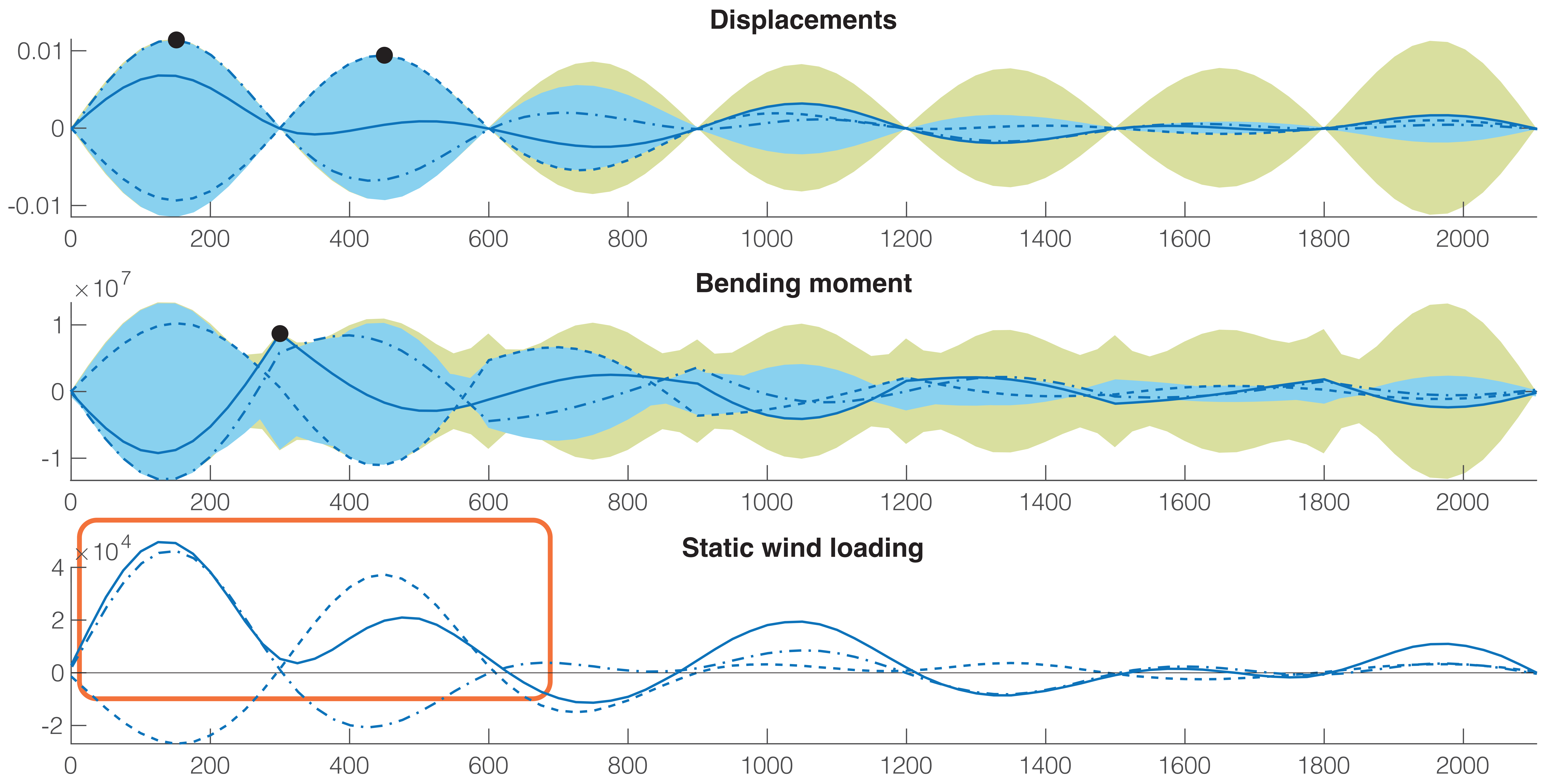
The Envelope Reconstruction Problem



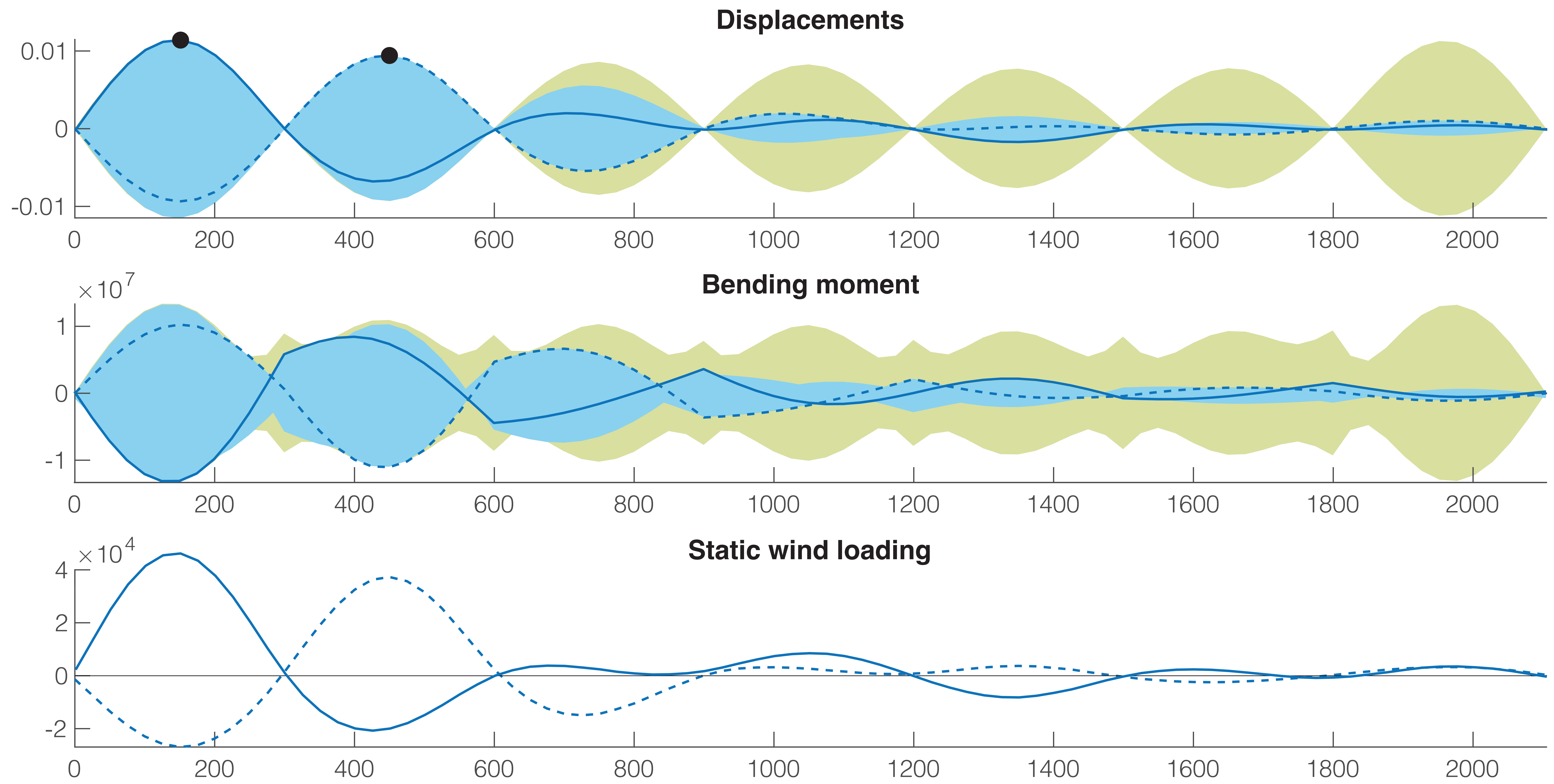
The Envelope Reconstruction Problem



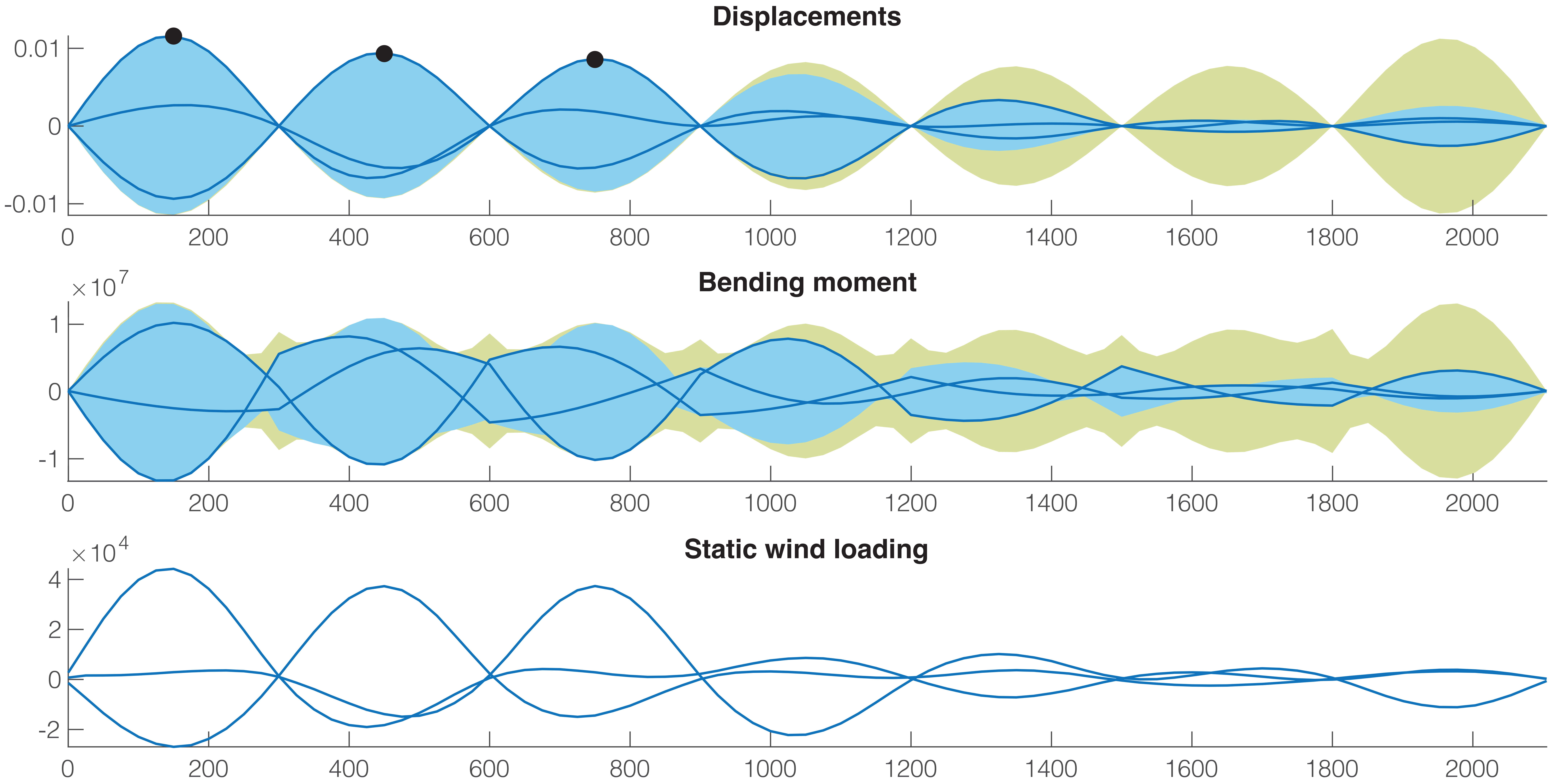
The Envelope Reconstruction Problem



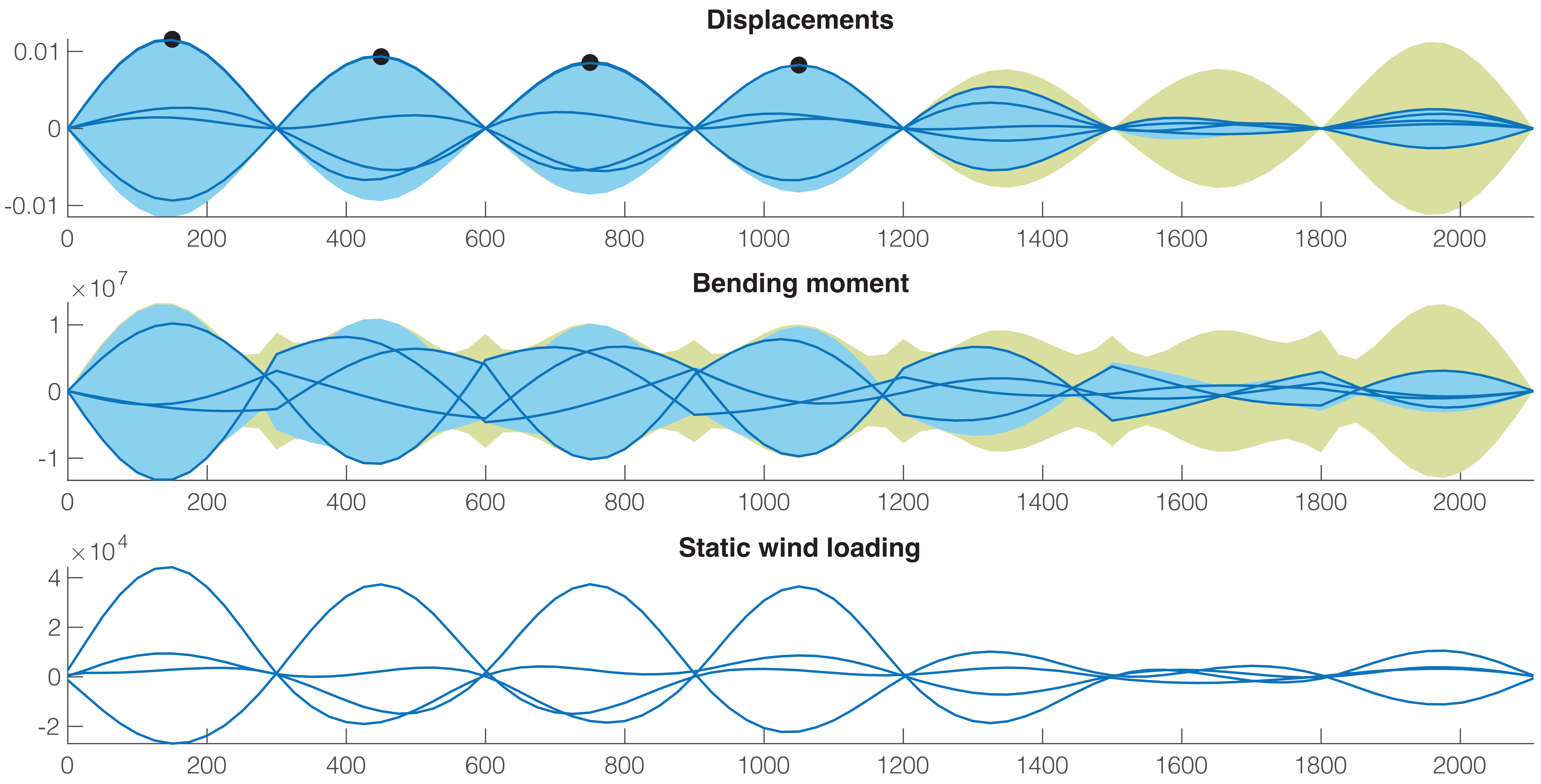
The Envelope Reconstruction Problem



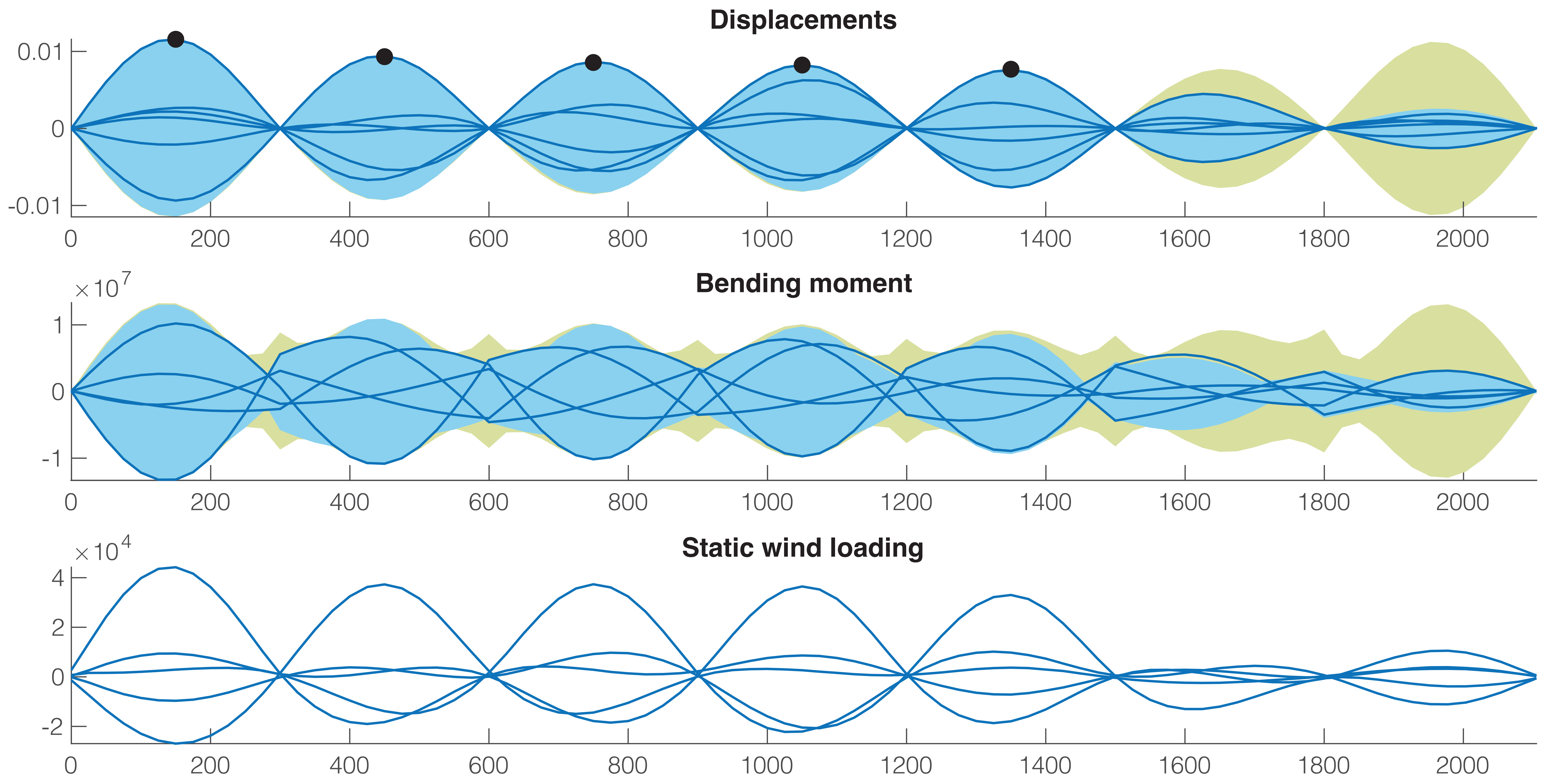
The Envelope Reconstruction Problem



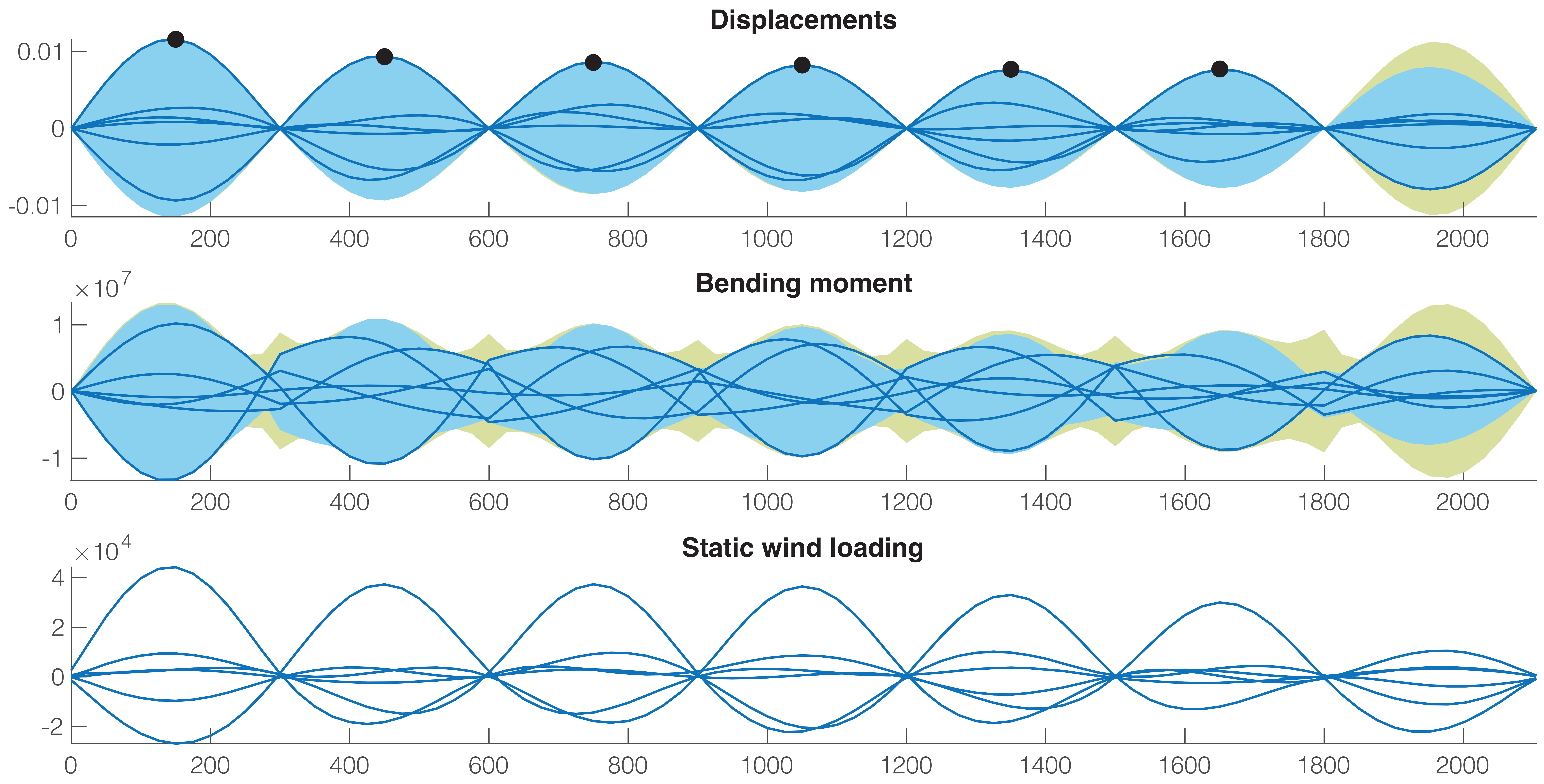
The Envelope Reconstruction Problem



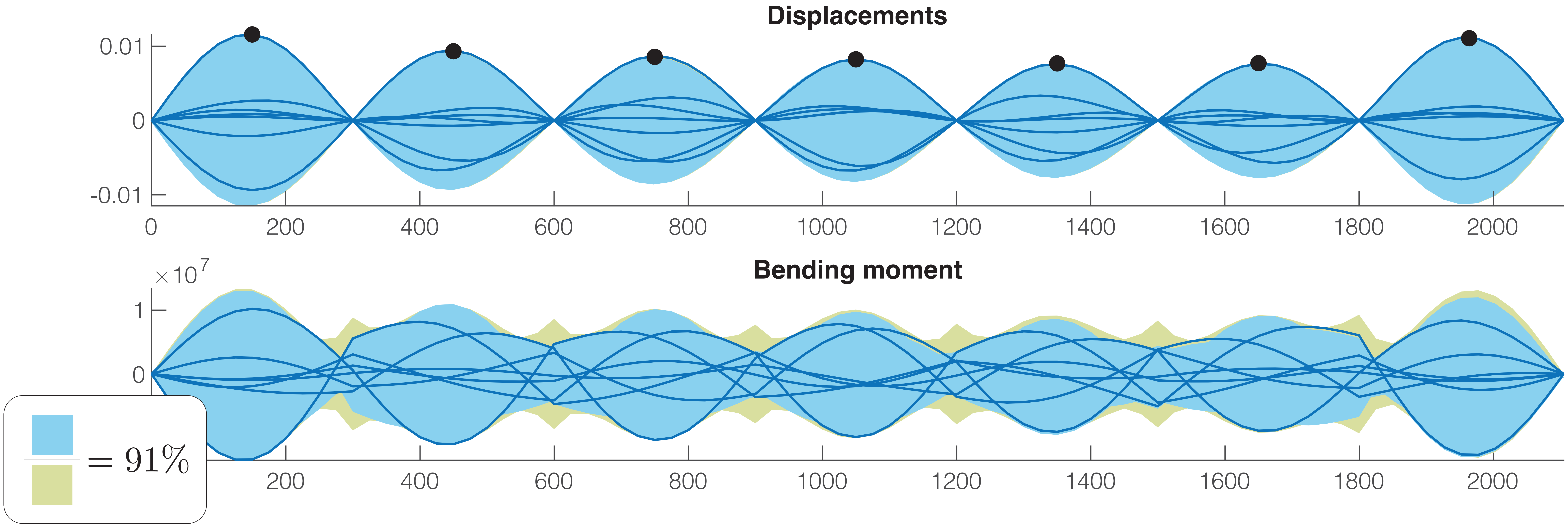
The Envelope Reconstruction Problem



The Envelope Reconstruction Problem



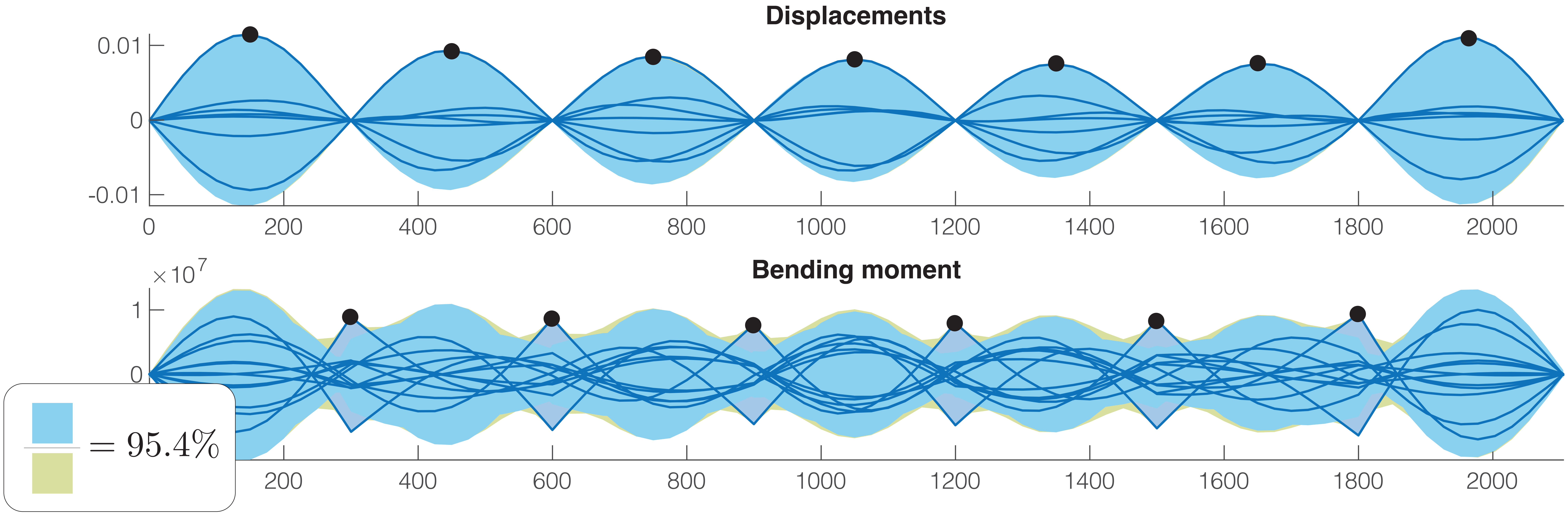
The Envelope Reconstruction Problem



Reconstruction of the envelopes with mid-span displacements only

Don’t try to reconstruct everything with displacements only

The Envelope Reconstruction Problem



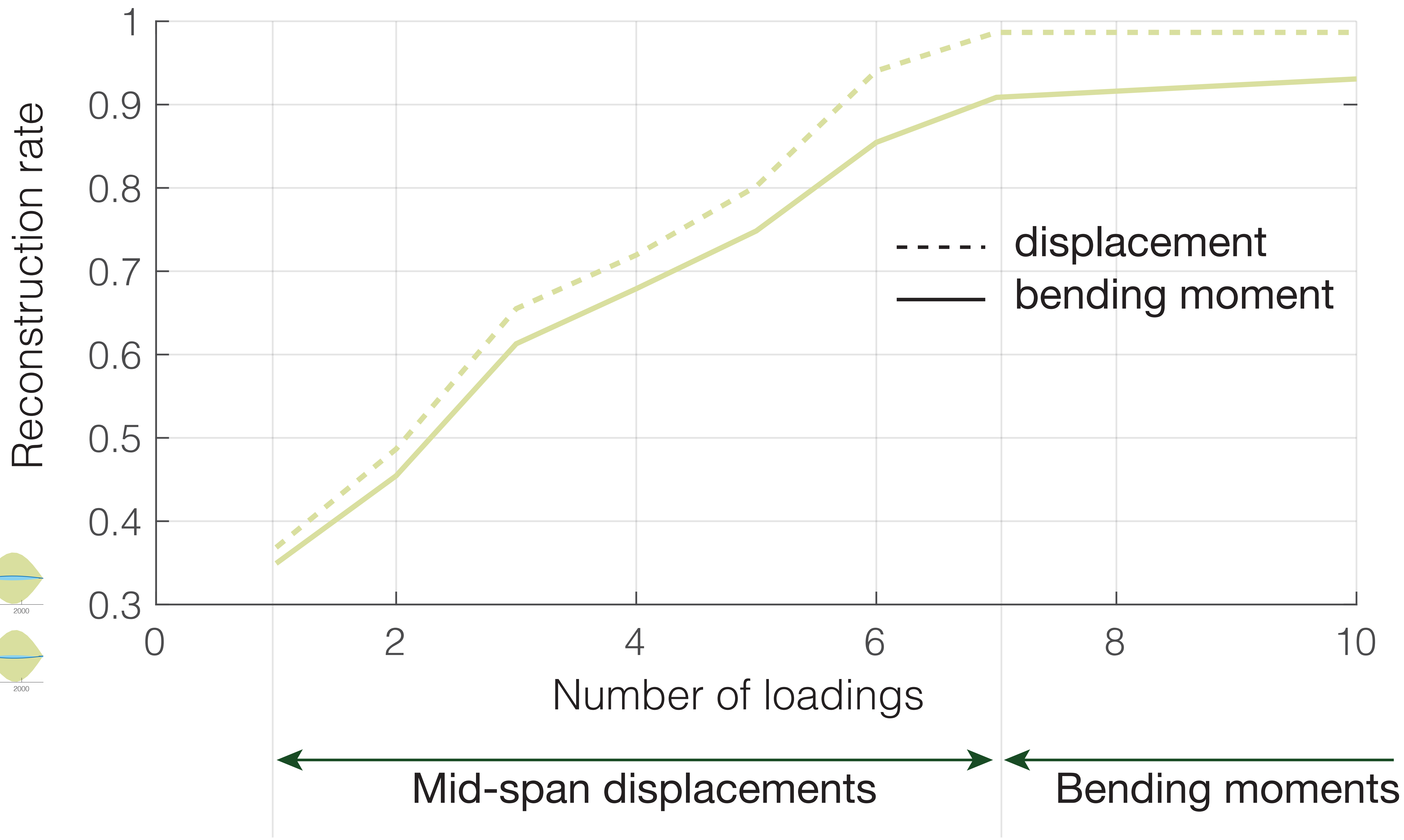
Reconstruction of the envelopes with : mid-span displacements

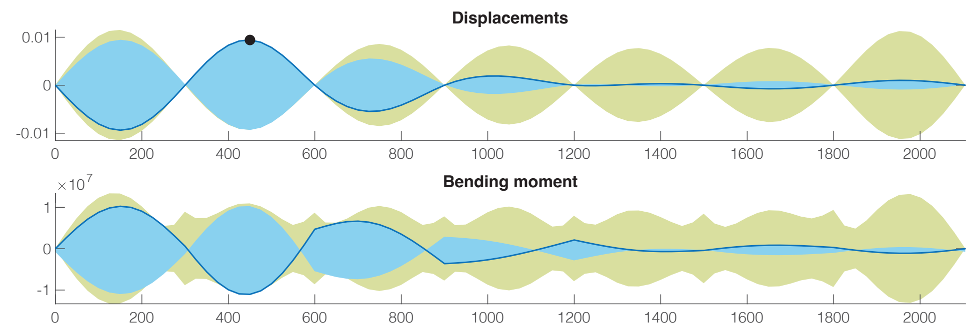
and bending moments on supports

The Envelope Reconstruction Problem

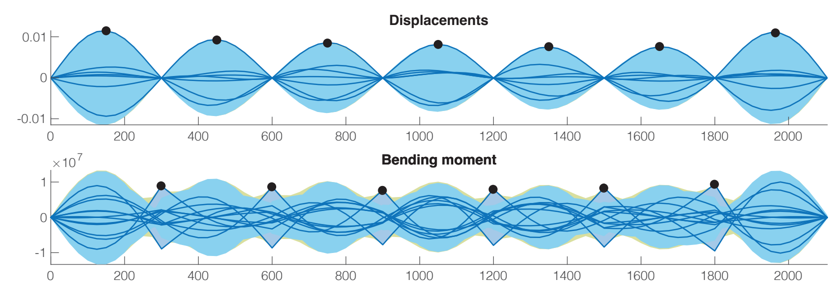
We used 13 ESWL.

1. Did we do a good job ? (NB: strength vs. loading)





(1 ESWL)



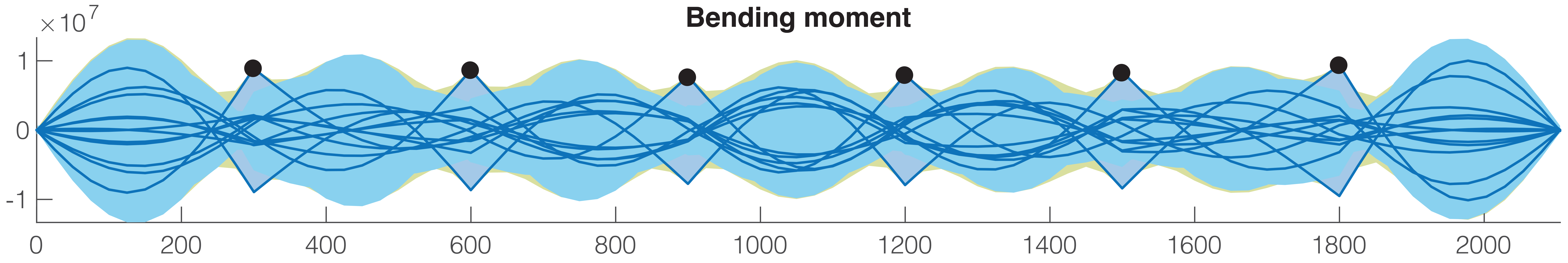
(13 ESWLs)

The Envelope Reconstruction Problem

We used 13 ESWL.

1. Did we do a good job ? (NB: strength vs. loading)
2. Could we be more efficient ? Use12 ESWL ? Or less ?
3. Nb. of ESWL vs. complexity. Why 13 ESWL ?
4. Difficulty to identify the « best » responses

$$\mathbf{z} = \begin{pmatrix} x_1 \\ \vdots \\ x_n \\ M_1 \\ \vdots \\ M_n \end{pmatrix}$$



The Envelope Reconstruction Problem

The Envelope Reconstruction Problem

Envelope : (generous) set of structural responses $\mathbf{z}_{\max}$: axial forces, bending moments, displacements, ground reactions, …

Reconstruction : isn't that clear ? (no matter origin of envelop — dynamic or not)

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}$$

$$\mathbf{z}(t) = \mathbf{A}\mathbf{x}(t) \qquad \mathbf{z}_{\max} = \max_t \mathbf{z}(t)$$

Find $\mathbf{f}_{\mathrm{E}}$ such that: $\mathbf{K}\mathbf{x}_{\mathrm{E}} = \mathbf{f}_{\mathrm{E}}$ and $\mathbf{A}\mathbf{x}_{\mathrm{E}} = \mathbf{z}_{\max}$

Find $\{\mathbf{f}_{\mathrm{E},i}\}$ such that, for $\mathbf{K}\mathbf{x}_{\mathrm{E},i} = \mathbf{f}_{\mathrm{E},i}$, $\mathbf{A}\mathbf{x}_{\mathrm{E},i} = \mathbf{z}_{\max,i}$,

and $\hat{\mathbf{z}}_{\max} = \max_{i=1,\cdots,n} \left|\mathbf{z}_{\max,i}\right|$

$\left\|\mathbf{z}_{\max} - \hat{\mathbf{z}}_{\max}\right\|$ is minimum

Some considerations

Envelope : (generous) set of structural responses : axial forces, bending moments, displacements, ground reactions, …

Which envelope ? Absolute, Relative values, Units (!?), Consider strength.

Constraints : the $\{\mathbf{f}_{\mathrm{E},i}\}$ should look realistic

the number of ESWL should not be too large (but it depends on the complexity)

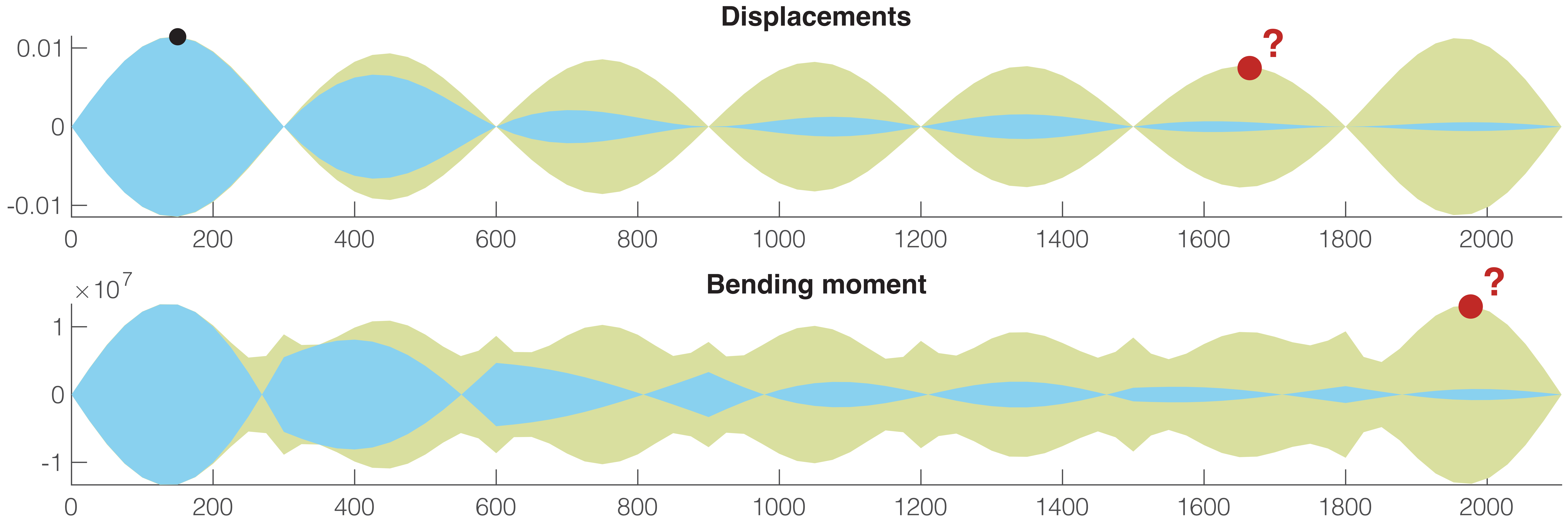
Freedom : maybe allow for some over-estimation / under-estimation

Find $\{\mathbf{f}_{\mathrm{E},i}\}$ such that, for $\mathbf{K}\mathbf{x}_{\mathrm{E},i} = \mathbf{f}_{\mathrm{E},i}$, $\mathbf{A}\mathbf{x}_{\mathrm{E},i} = \mathbf{z}_{\max,i}$,

and $\hat{\mathbf{z}}_{\max} = \max\limits_{i=1,\cdots,n} \left|\mathbf{z}_{\max,i}\right|$

$\left\|\mathbf{z}_{\max} - \hat{\mathbf{z}}_{\max}\right\|$ is minimum

Adaptive Descent solution



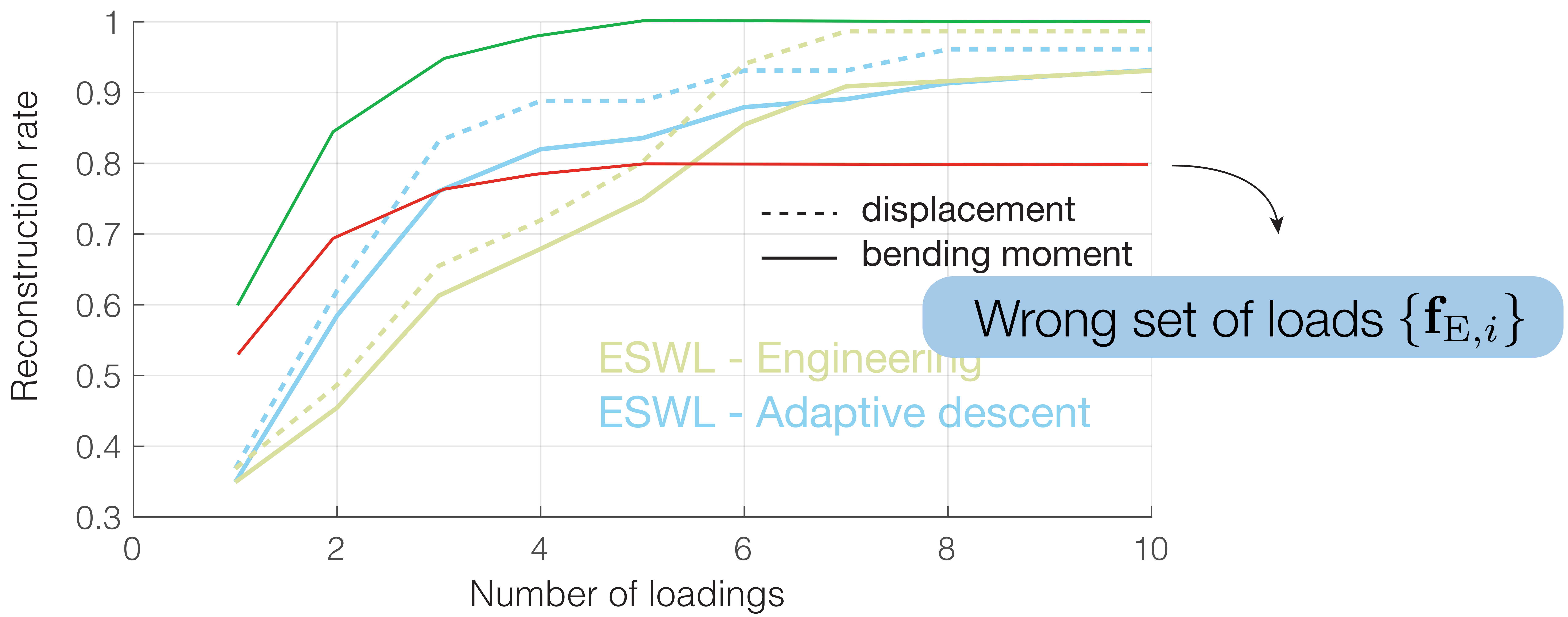
Step 1 : consider 1 major response & associated ESWL

Step 2 : find worst reconstructed response

Step 3 : define new ESWL & iterate

NB: needs a starting point

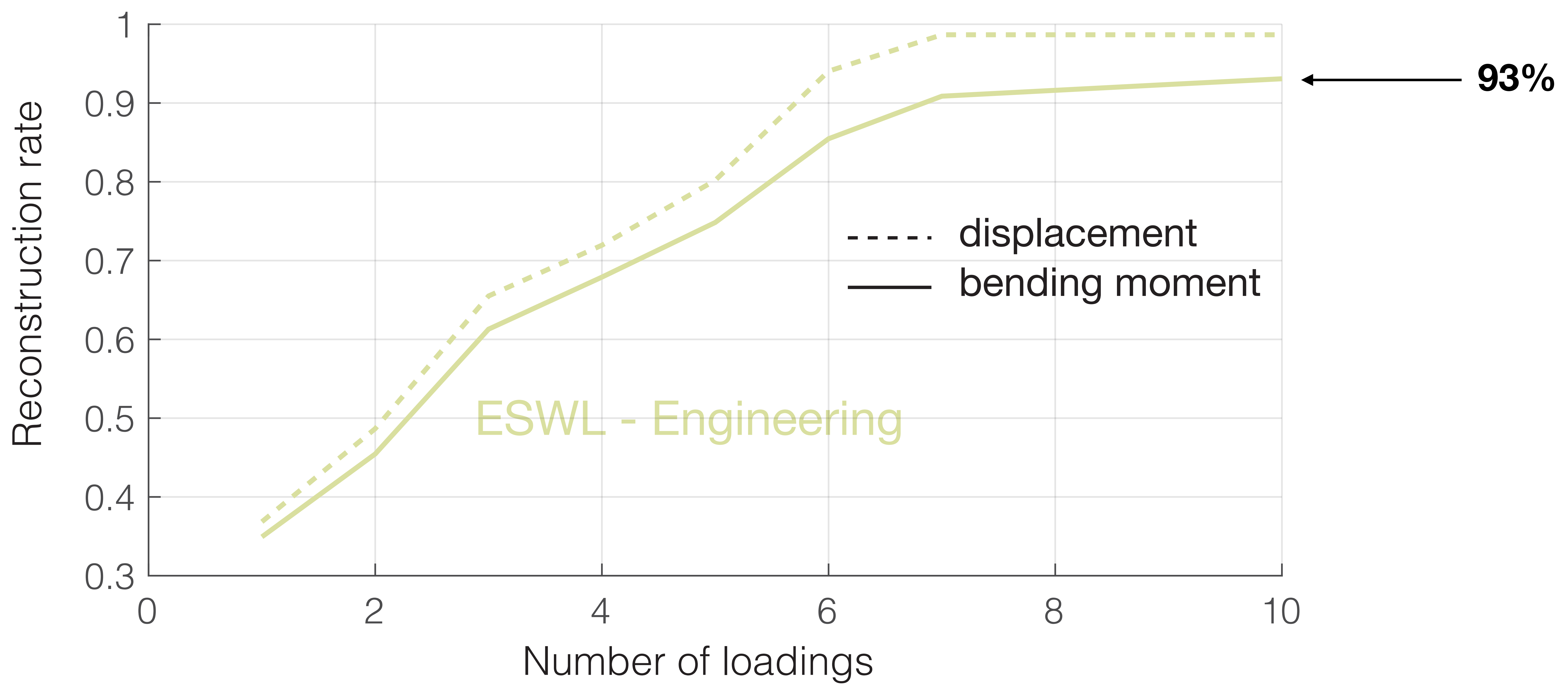
Envelope reconstruction rate

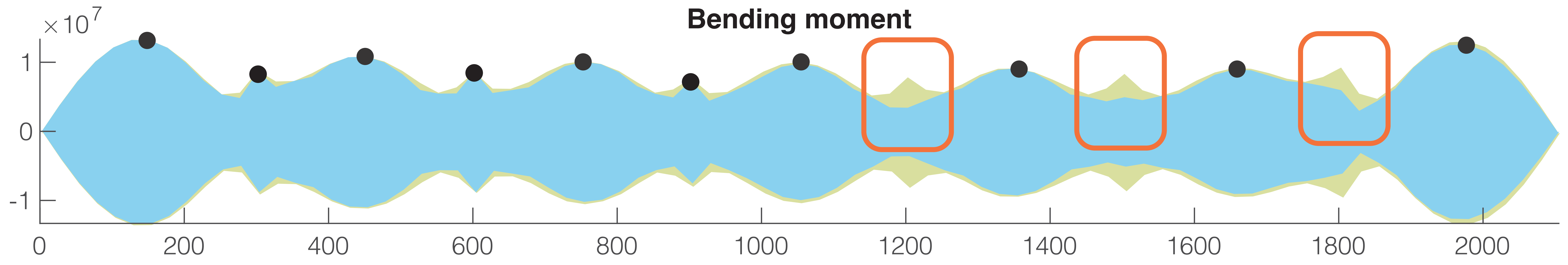


Quality of a good reconstruction algorithm :

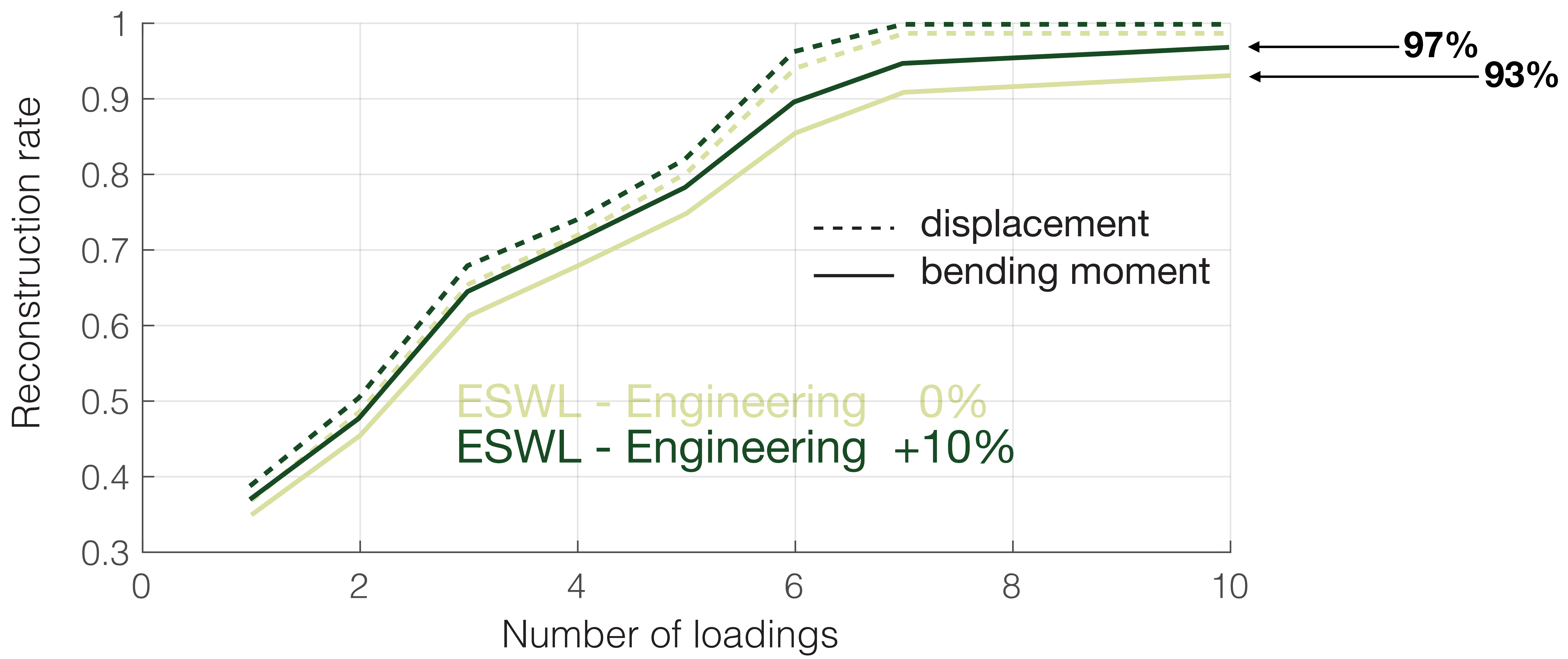
- fast convergence
- high terminal convergence rate

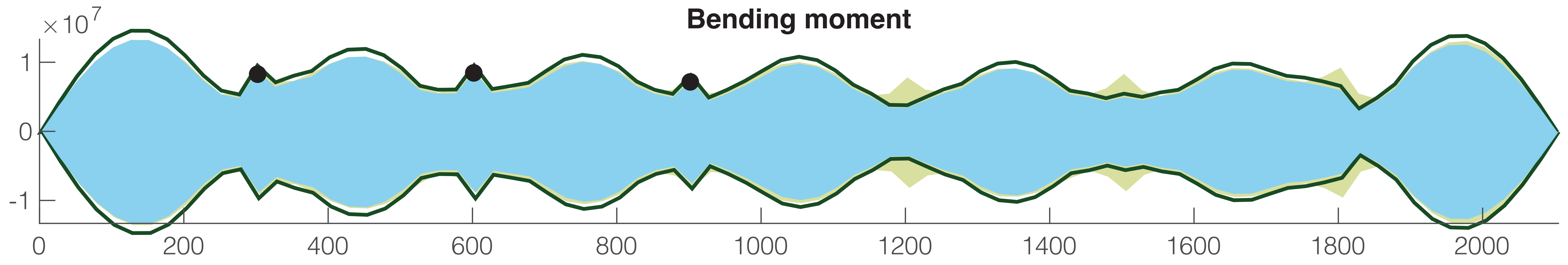
Our freedom: overestimation and underestimation



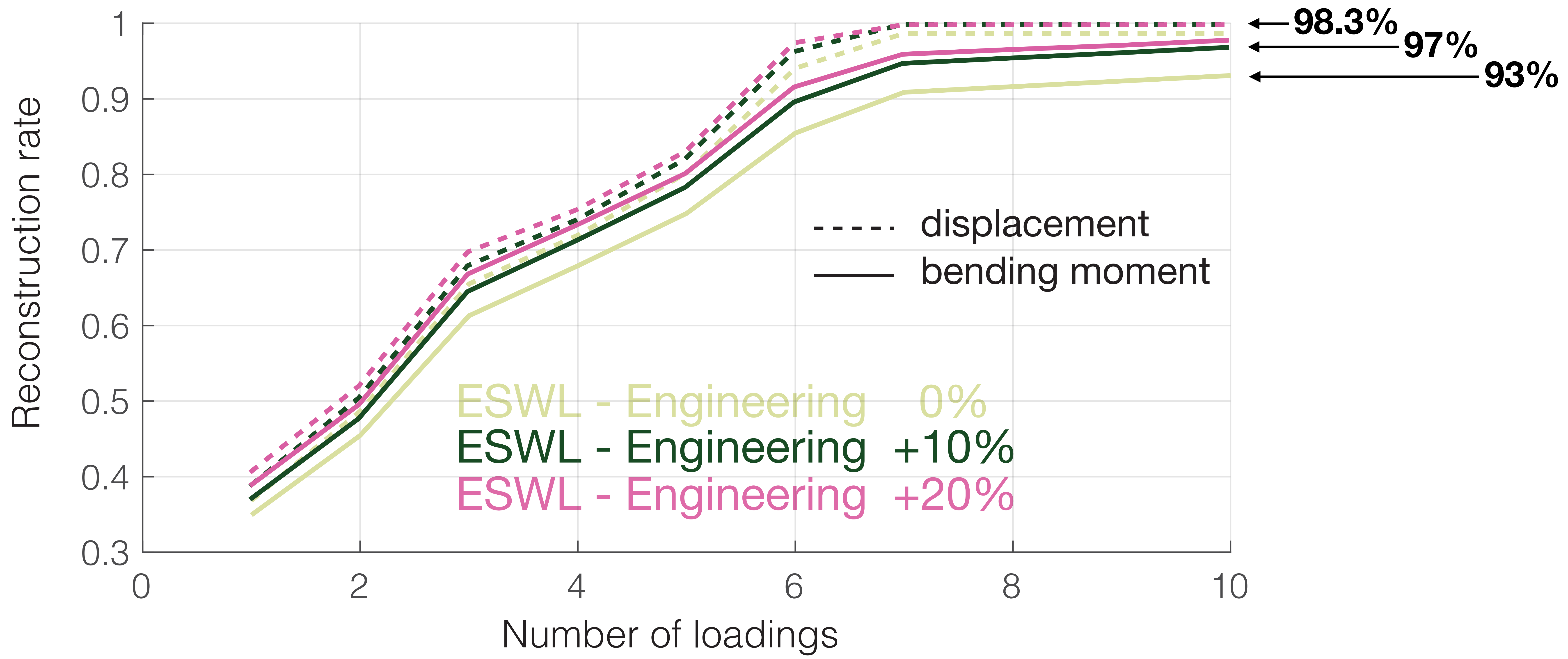


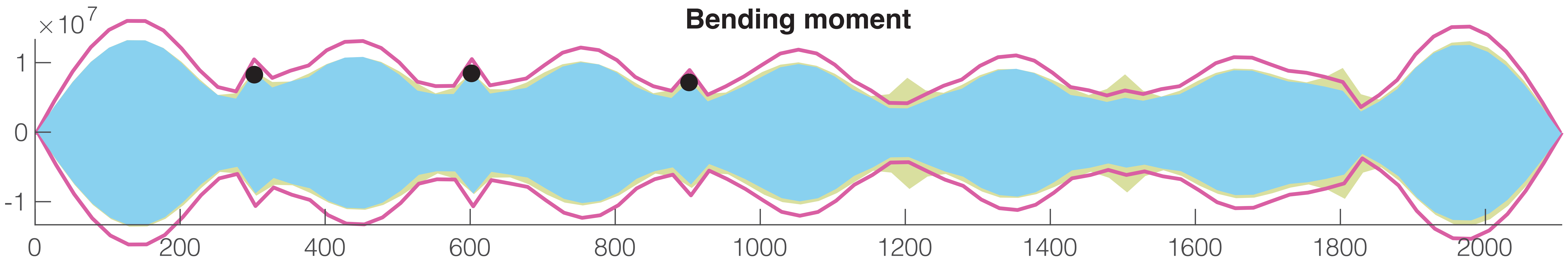
Our freedom: overestimation and underestimation





Our freedom: overestimation and underestimation





Our freedom: overestimation and underestimation

Find $\{\mathbf{f}_{\mathrm{E},i}\}$ such that, for $\mathbf{K}\mathbf{x}_{\mathrm{E},i} = \mathbf{f}_{\mathrm{E},i}$, $\mathbf{A}\mathbf{x}_{\mathrm{E},i} = \mathbf{z}_{\max,i}$,

and $\hat{\mathbf{z}}_{\max} = \max_{i=1,\cdots,n} |\mathbf{z}_{\max,i}|$

~~$\|\mathbf{z}_{\max} - \hat{\mathbf{z}}_{\max}\|$ is minimum~~

Underestimation :

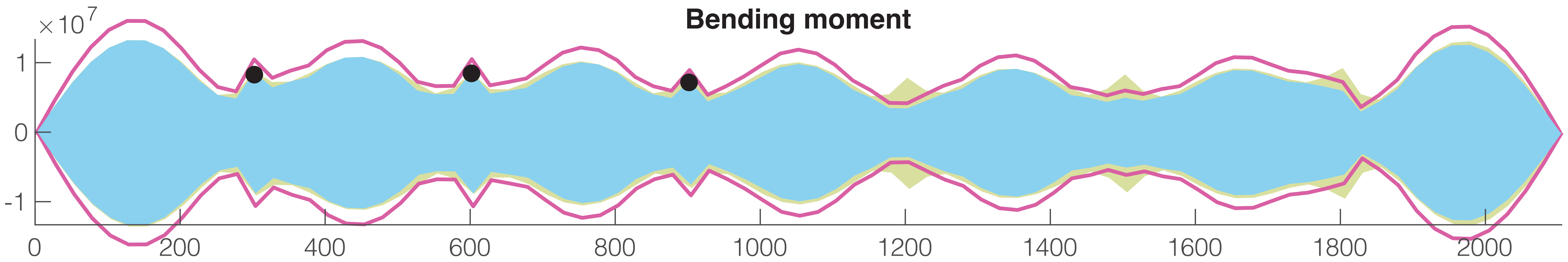
- could be accepted if smaller or secondary elements (but then, don't include them in responses)
- to be discussed with client

Overestimation :

- pay attention to excessive costs
- to be discussed with client

Envelope is reconstructed :

- within chosen/agreed over- and under-estimations (10%-20%)
- faster convergence rate



Timeline

1967

Gust Response Factor

Davenport, 1967

1992

Conditional Sampling
Load Response Correlation

Davenport 1985; Holmes 1992; Holmes and Kasperski 1996; Irwin 1998; Zhou et al. 2000

1985

Modal Inertial Loads

Davenport 1985; Irwin 1998; Holmes 1999; King 1999

1998

Background/Resonant
Conditional Expected Load

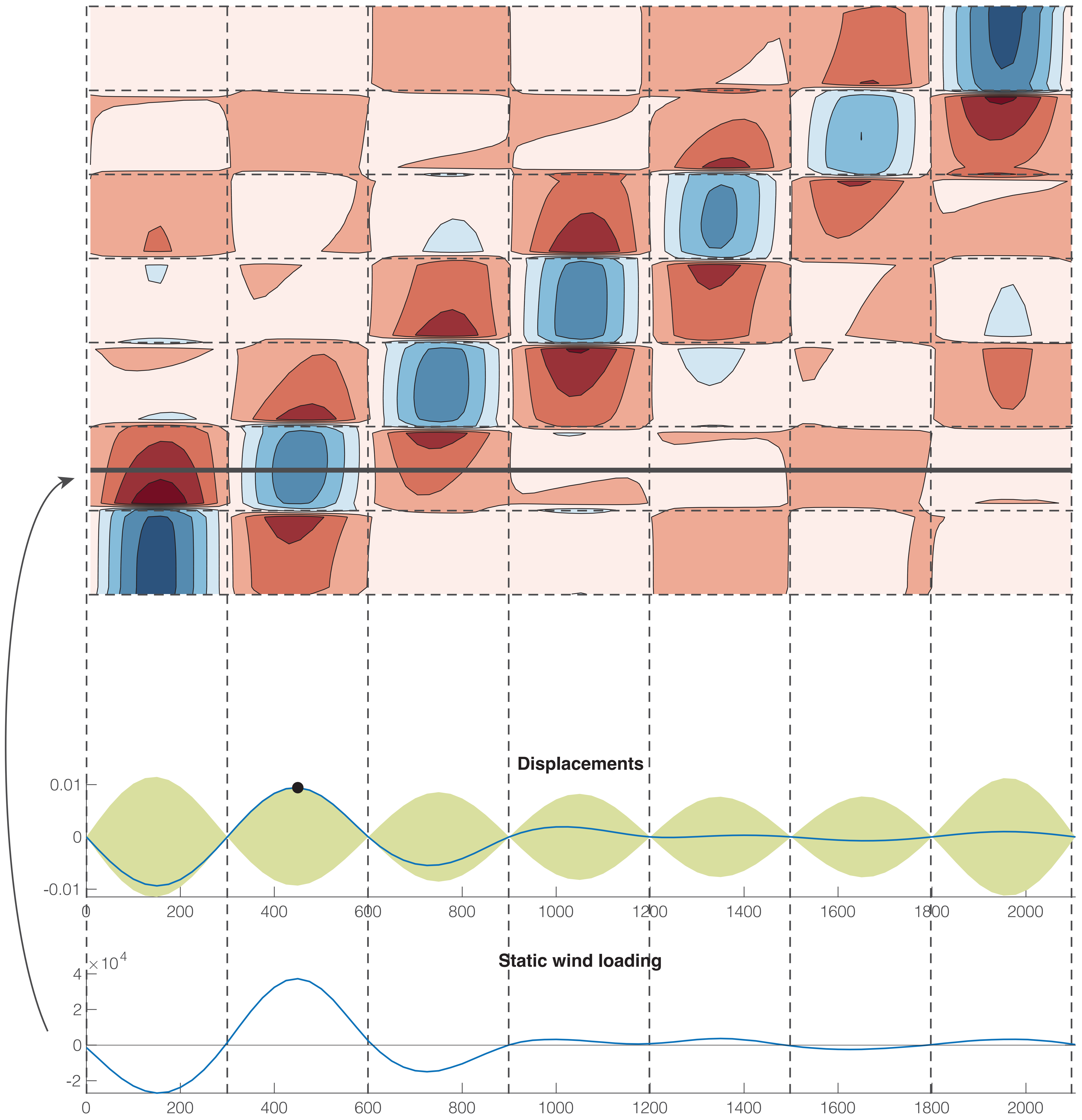
Irwin 1998; Holmes 1999; King 1999; Chen & Kareem (2001); Blaise and Denoël (2012XXX)

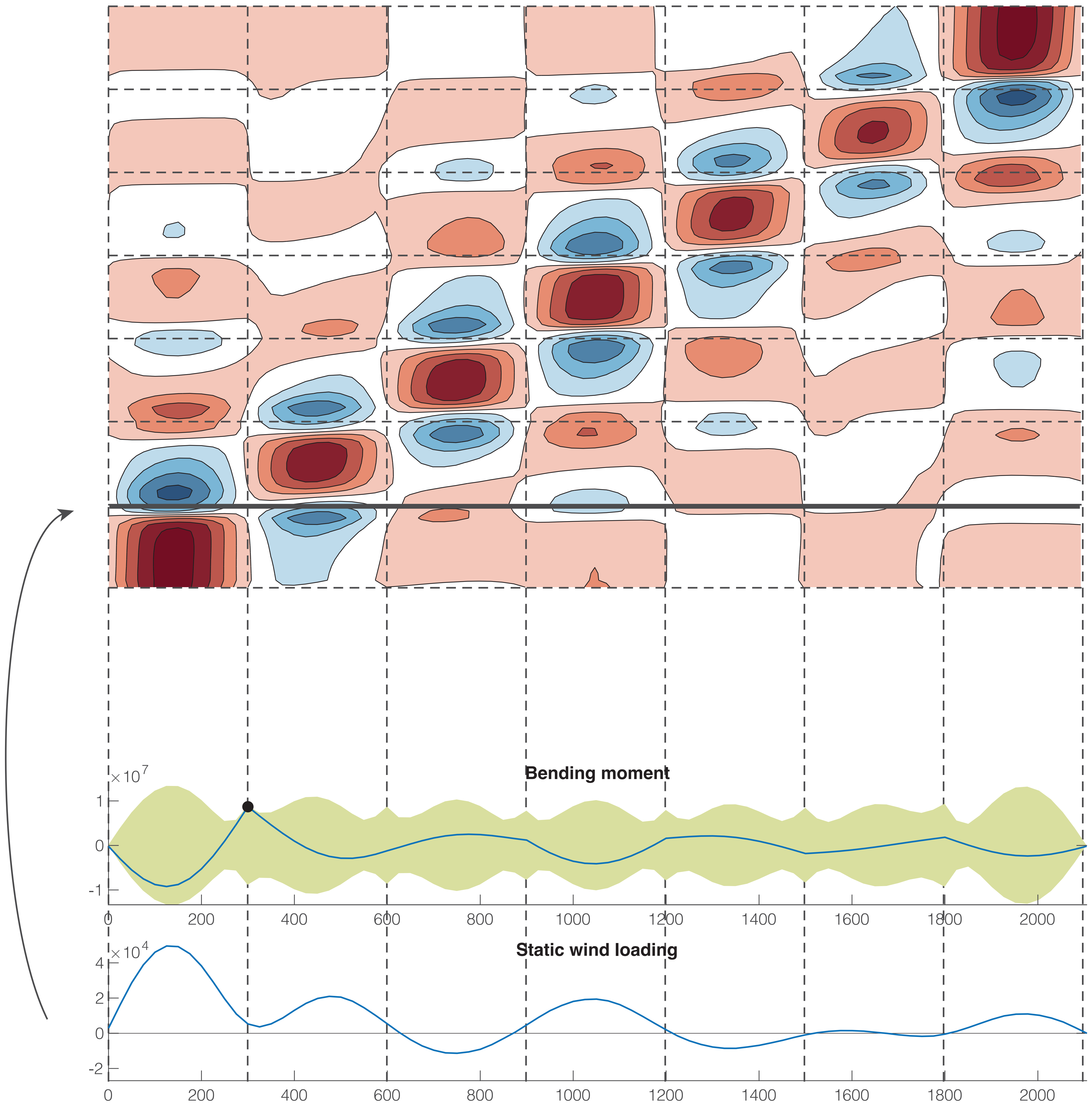
2004

Principal Static Wind Loads
Proper Skin Modes
Universal Wind Load

Katsumura, Tamura 2004-2007, Blaise, Denoël 2009-2014; Patruno et al. 2016

The basis of ESWLs





Principal static wind loads

PSWL

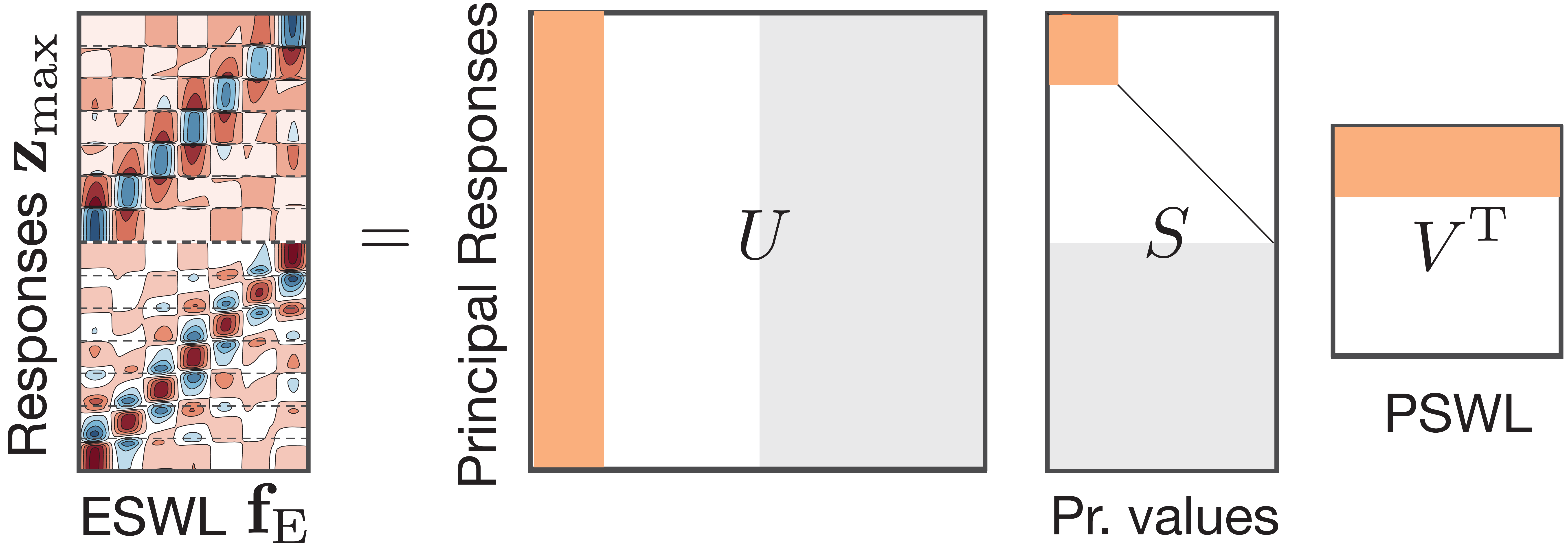
CPT

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}$$

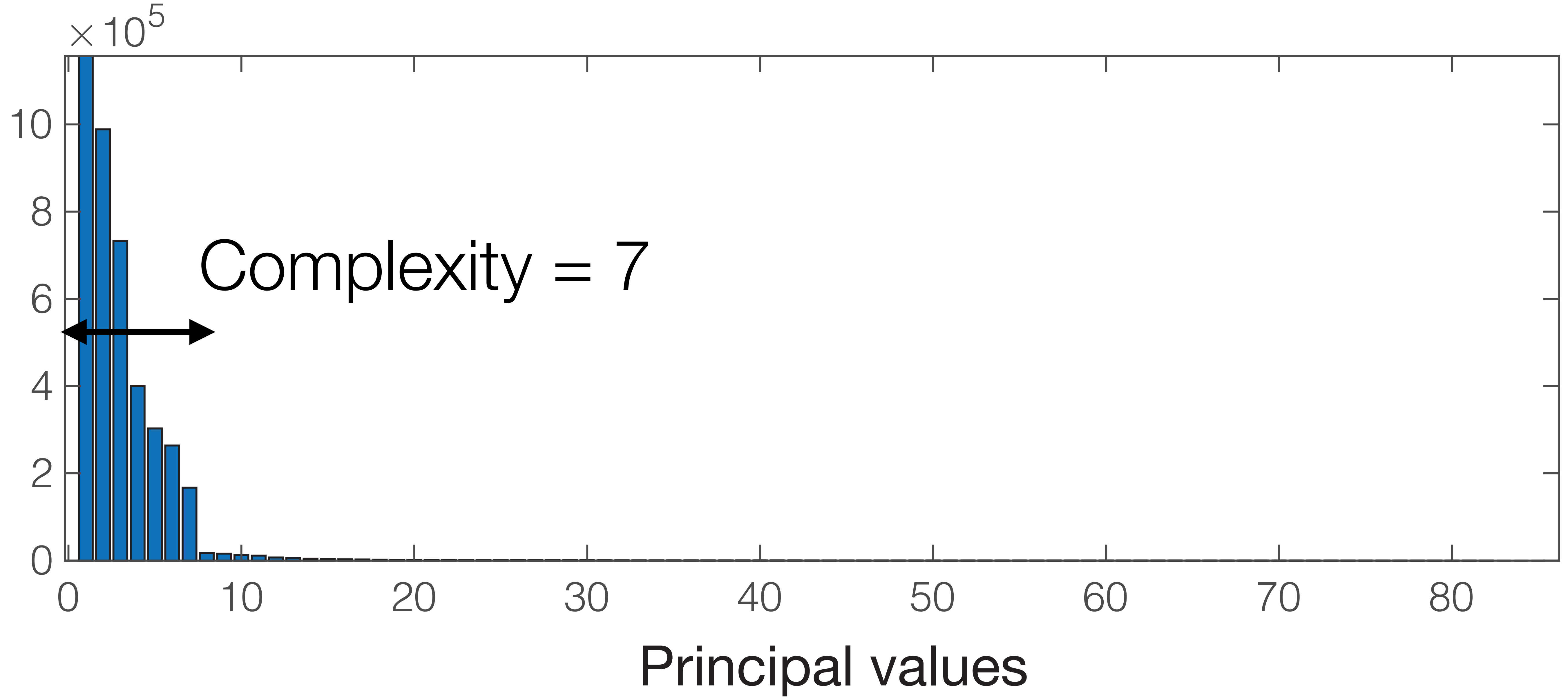
$$\mathbf{z}(t) = \mathbf{A}\mathbf{x}(t) \qquad \mathbf{z}_{\max} = \max_t \mathbf{z}(t)$$

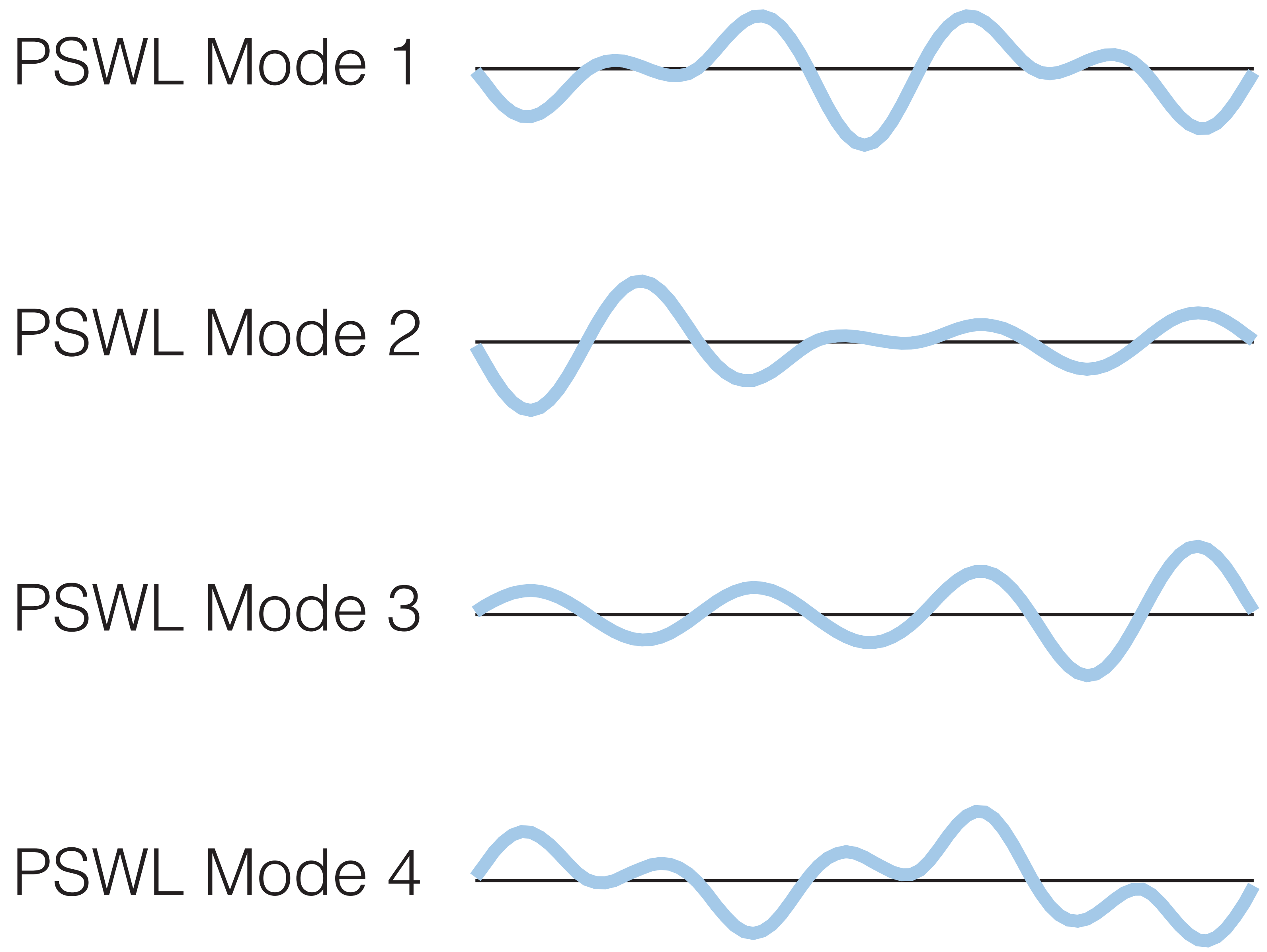
$$\mathbf{A}\mathbf{K}^{-1}\mathbf{f}_\mathrm{E} = \mathbf{z}_{\max}$$

Find $\mathbf{f}_\mathrm{E}$ such that: $\mathbf{K}\mathbf{x}_\mathrm{E} = \mathbf{f}_\mathrm{E}$ and $\mathbf{A}\mathbf{x}_\mathrm{E} = \mathbf{z}_{\max}$



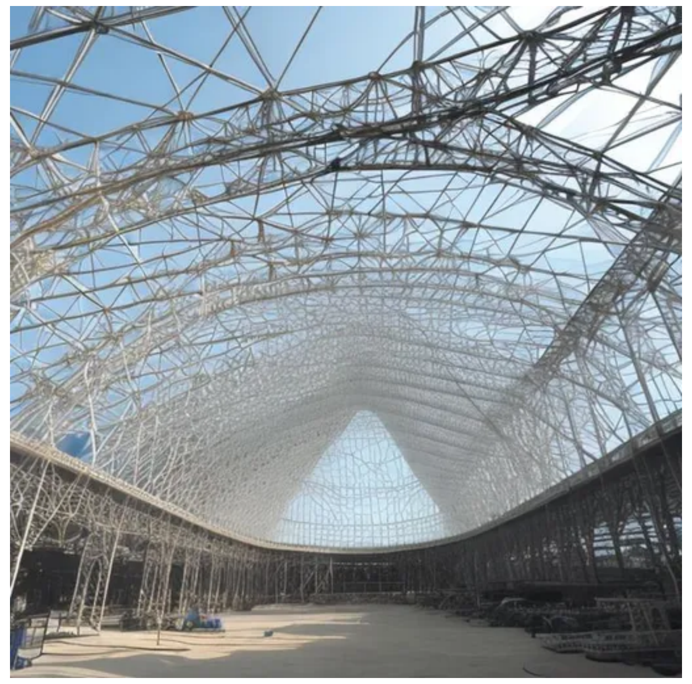
Principal static wind loads





Complexity = 1

Complexity = 2

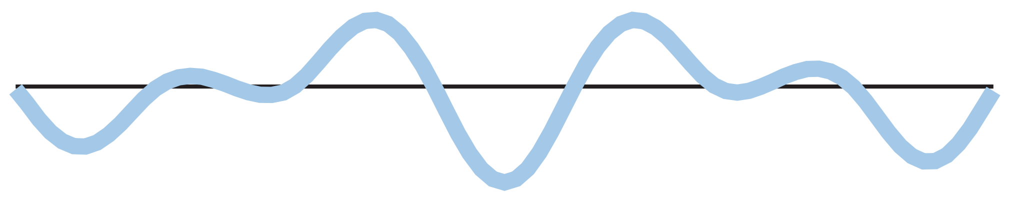


Complexity ~ 100-500

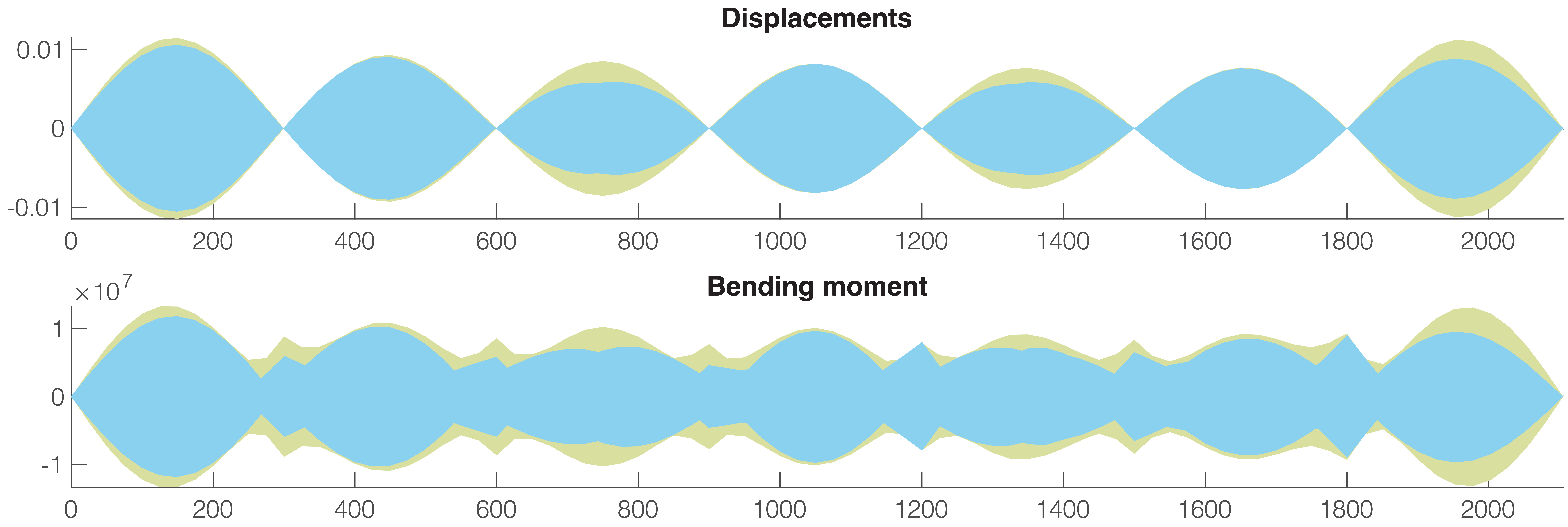
- PSWLs are affected by the nature of the response, i.e. Background or Resonant
- PSWLs, ***as such***, are not necessarily optimum to reconstruct the envelope

Principal static wind loads

PSWL Mode 1

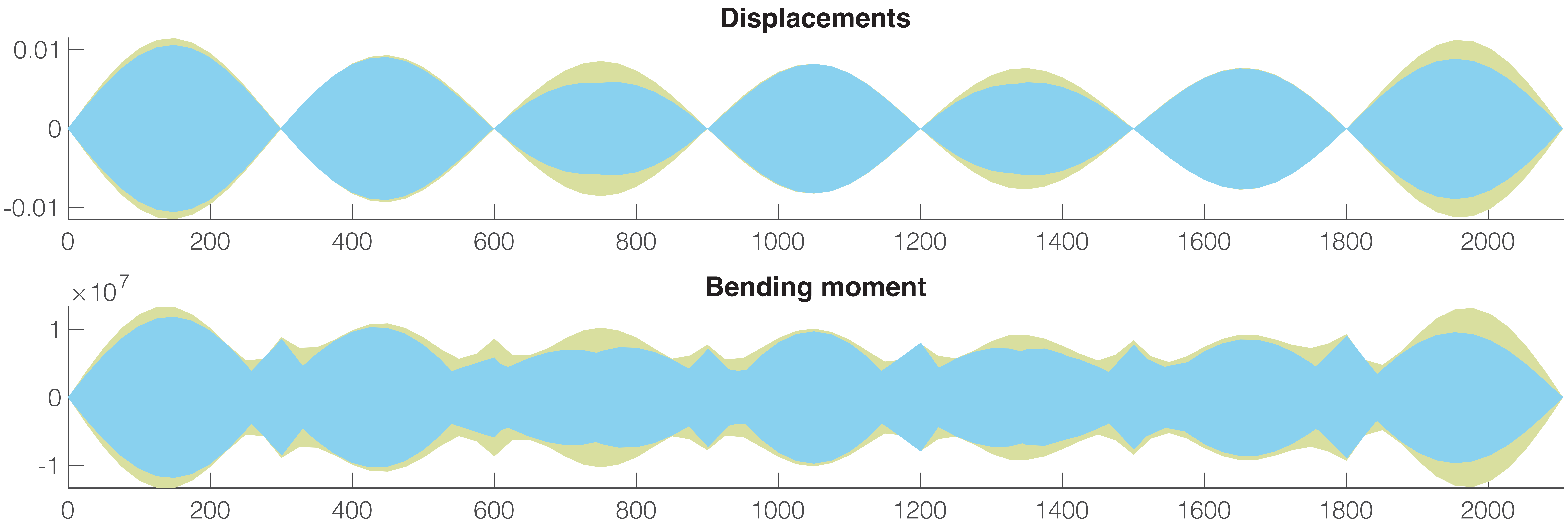


PSWL 1 & 2 & 3 & 4

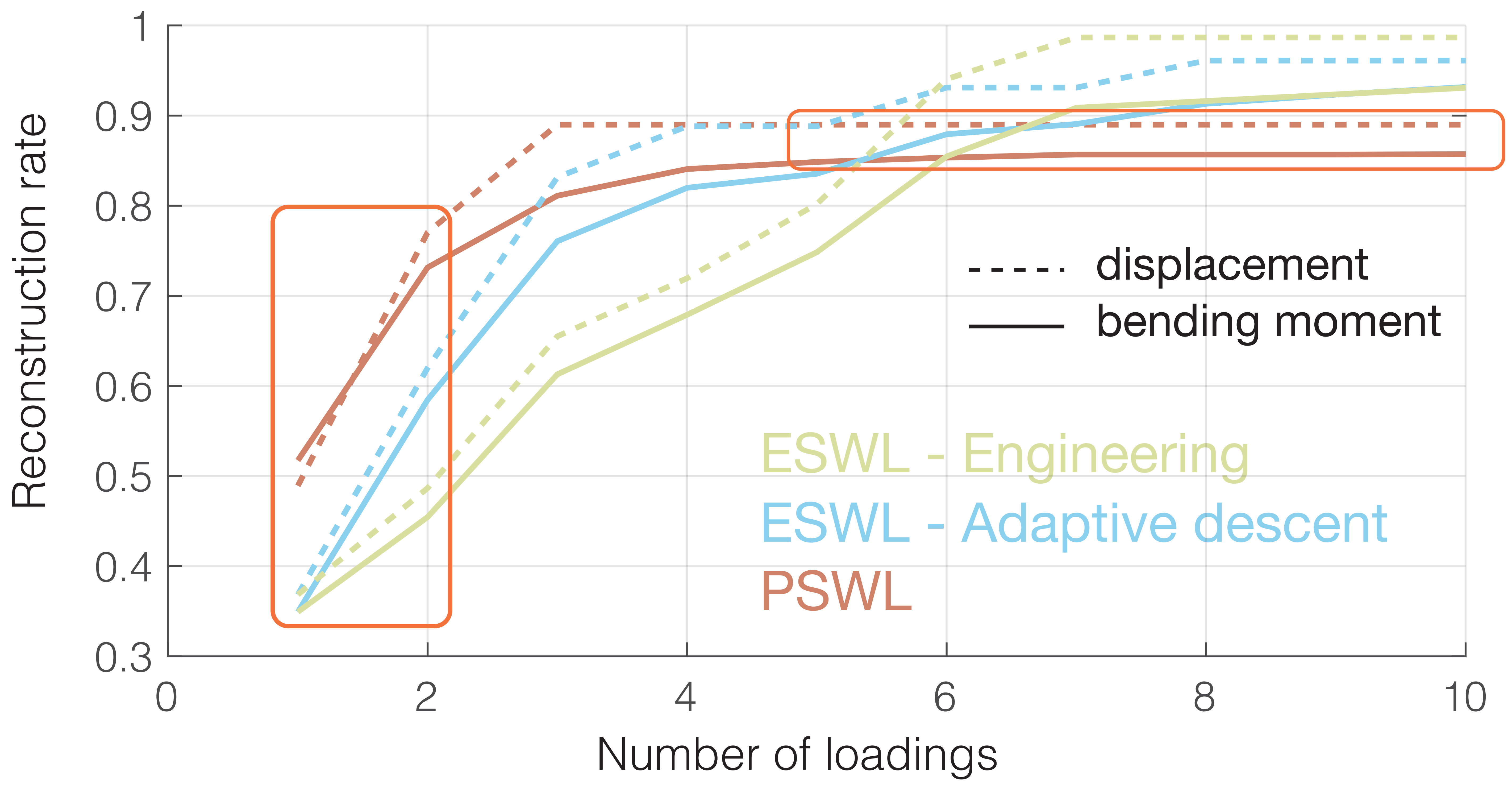


Principal static wind loads

PSWL 1 to 7



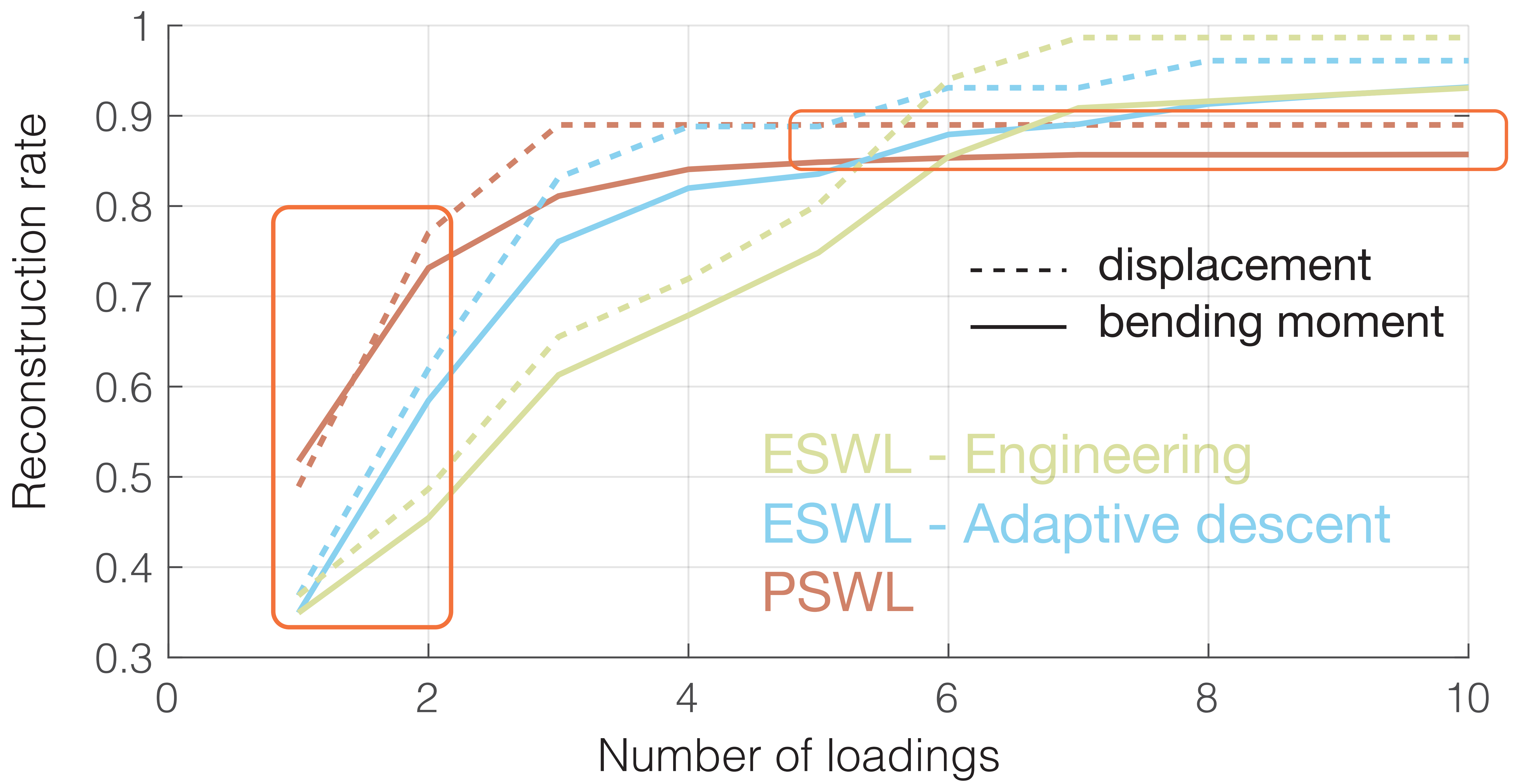
Principal static wind loads



Observations : very good start, as expected

poor terminal reconstruction rate

Principal static wind loads



Solutions :

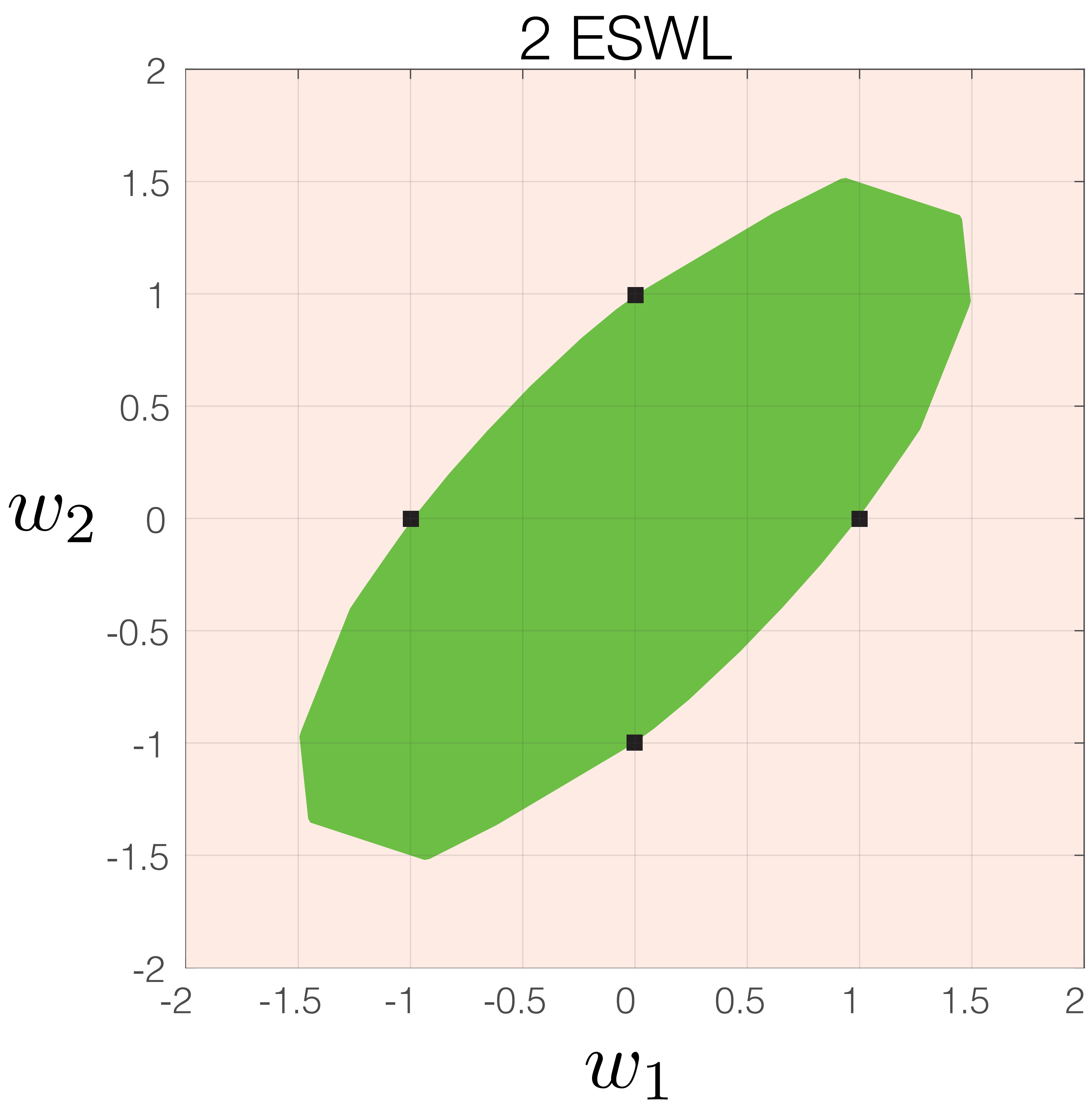
(i) allow some over-estimation - TBD with clients

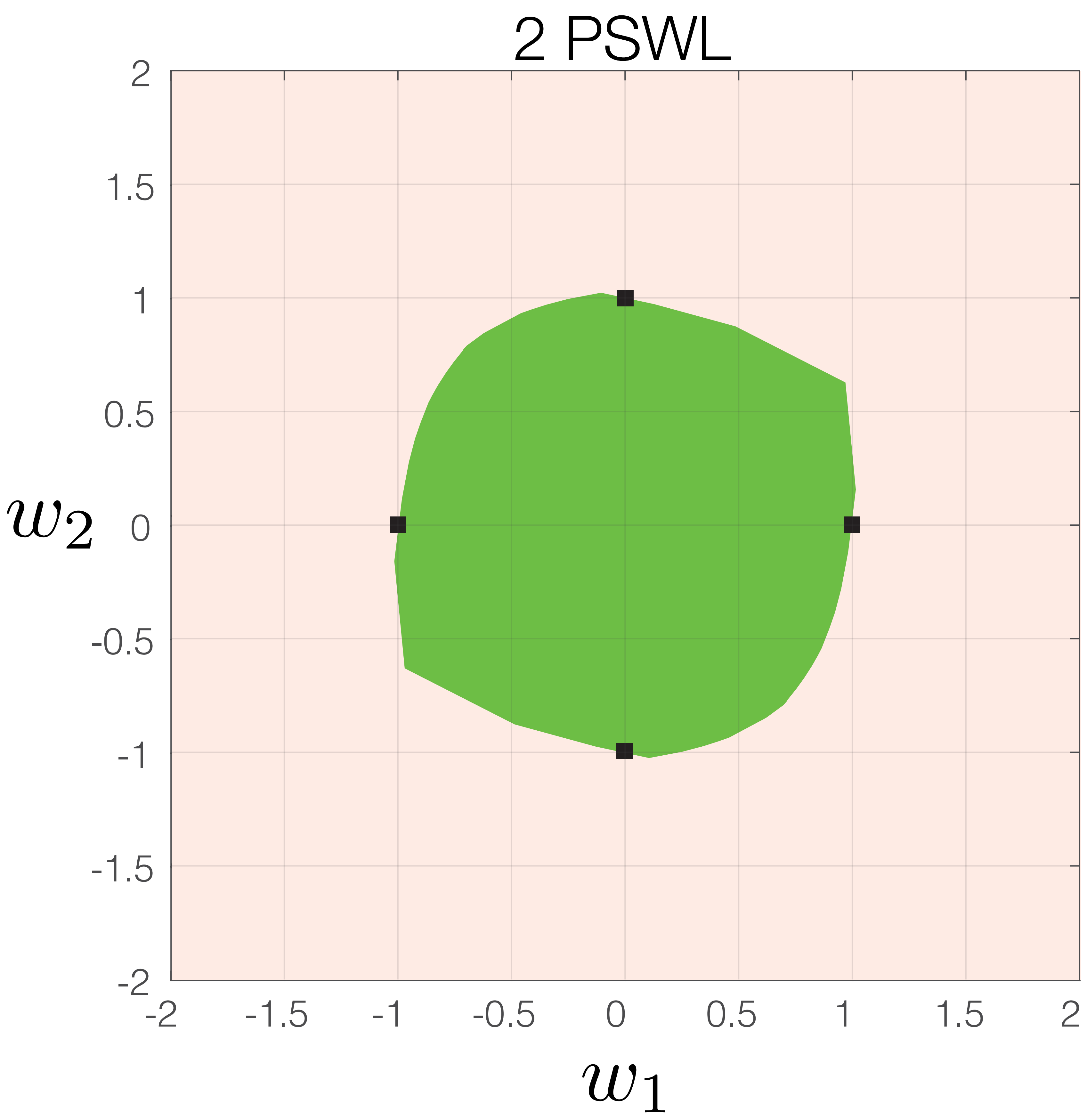
(ii) use some PSWLs, then Adaptive descent

(iii) **(linearly) combine PSWLs**

Principal static wind loads

Acceptable range of values for combination coefficients



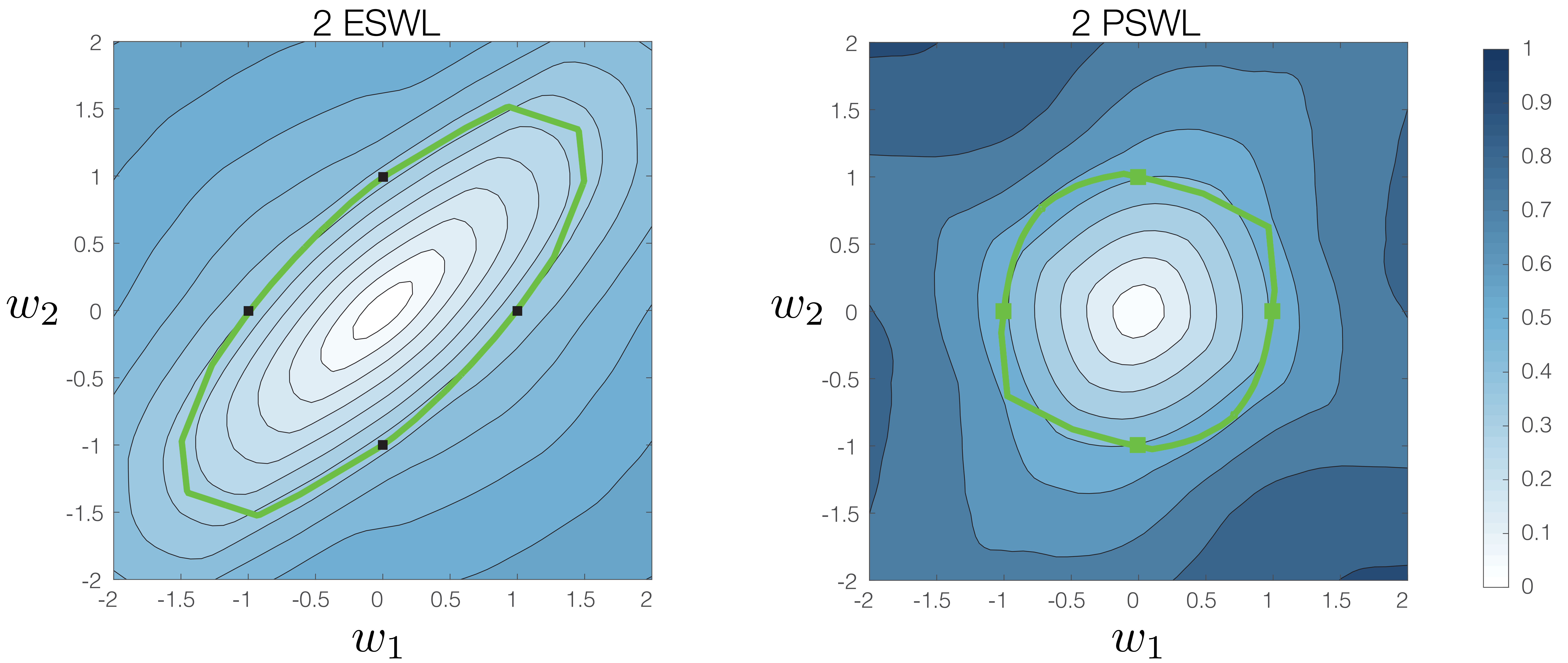


$$\mathbf{f}_{\mathrm{E}} = w_1 \mathbf{f}_{\mathrm{E},1} + w_2 \mathbf{f}_{\mathrm{E},2}$$

$$\mathbf{f}_{\mathrm{E}} = w_1 \mathbf{f}_{\mathrm{E},1}^{\mathrm{PSWL}} + w_2 \mathbf{f}_{\mathrm{E},2}^{\mathrm{PSWL}}$$

Principal static wind loads

Reconstruction rate

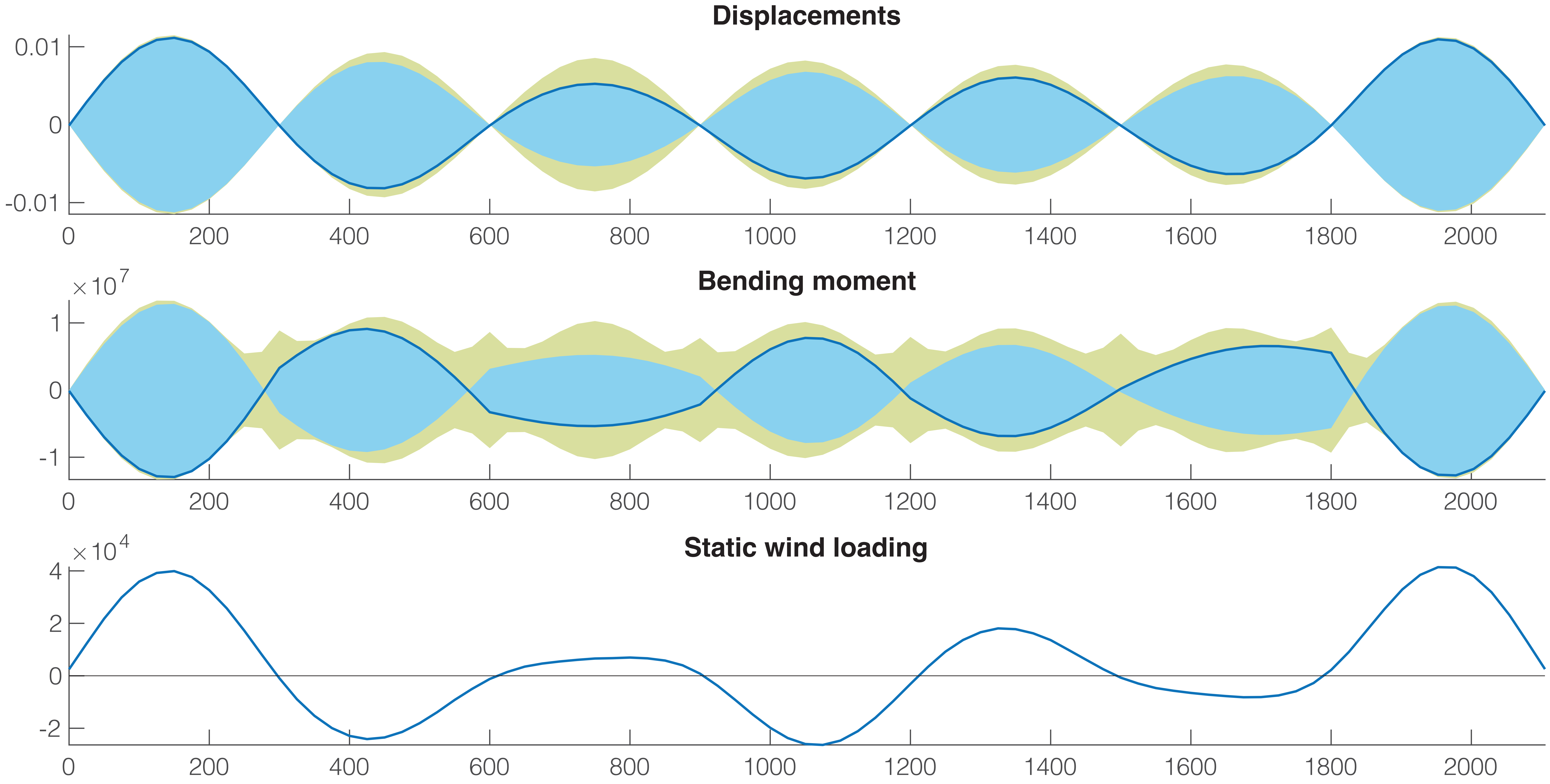


$$\mathbf{f}_{\mathrm{E}} = w_1 \mathbf{f}_{\mathrm{E},1} + w_2 \mathbf{f}_{\mathrm{E},2}$$

$$\mathbf{f}_{\mathrm{E}} = w_1 \mathbf{f}_{\mathrm{E},1}^{\mathrm{PSWL}} + w_2 \mathbf{f}_{\mathrm{E},2}^{\mathrm{PSWL}}$$

Principal static wind loads

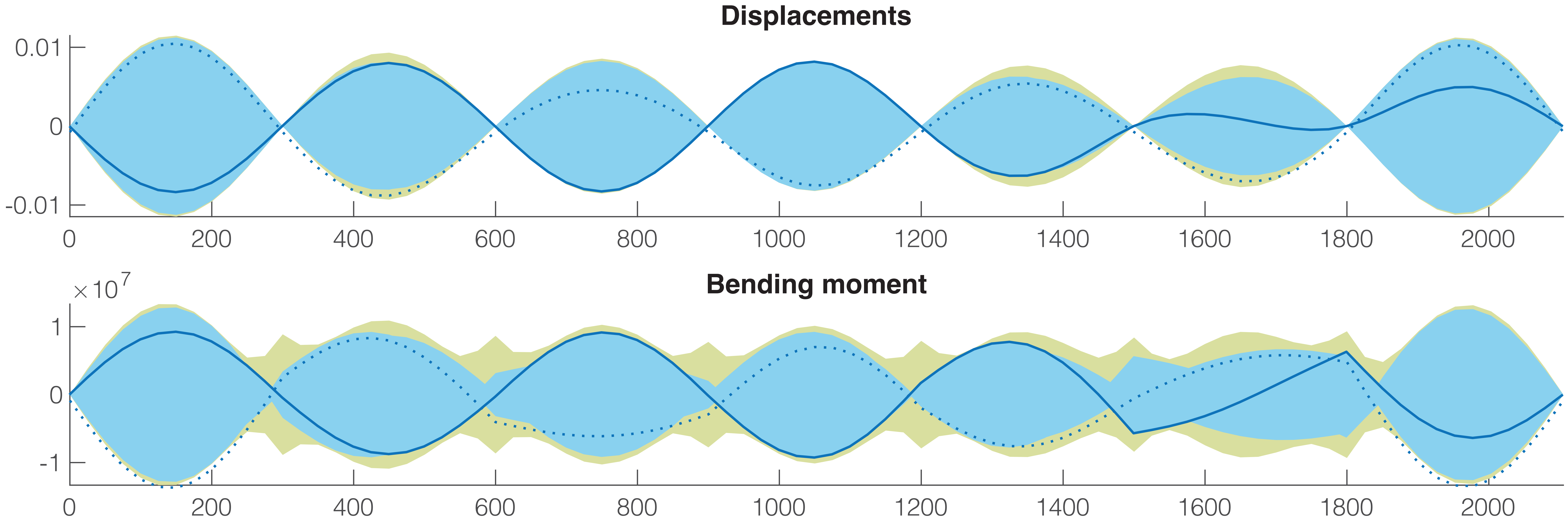
Combination of the first 7 PSWLs



Comb. 1
-0.16
-0.45
1.00
-0.04
0.31
-0.38
-0.14

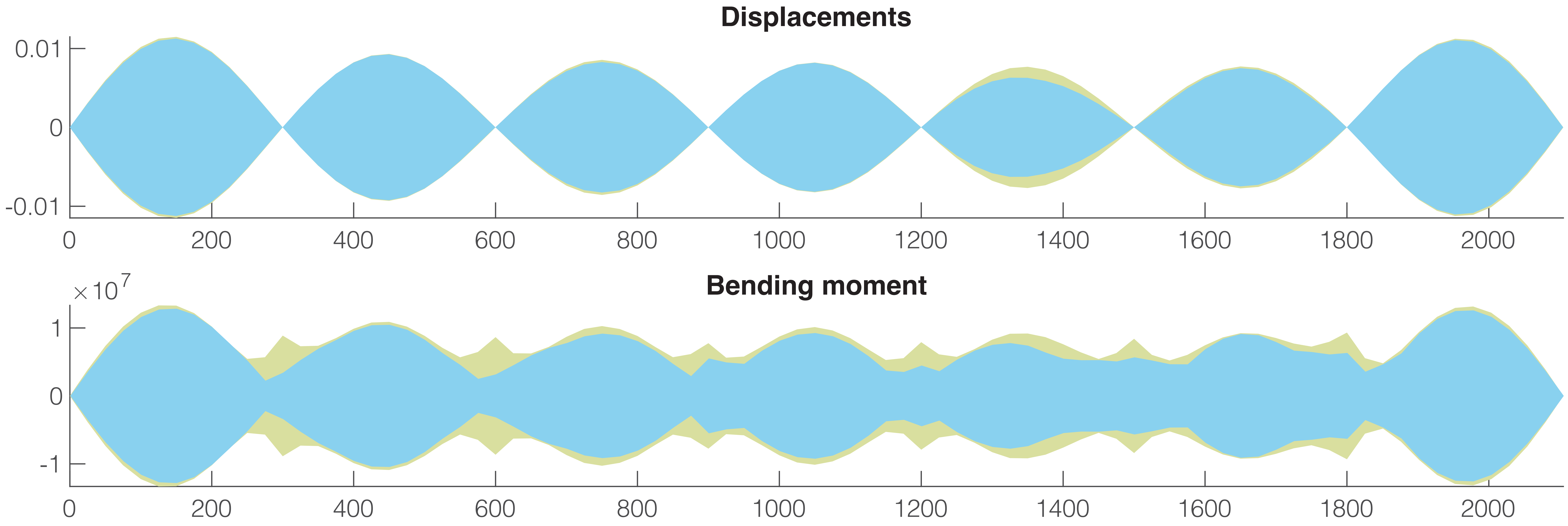
Principal static wind loads

Combination of the first 7 PSWLs



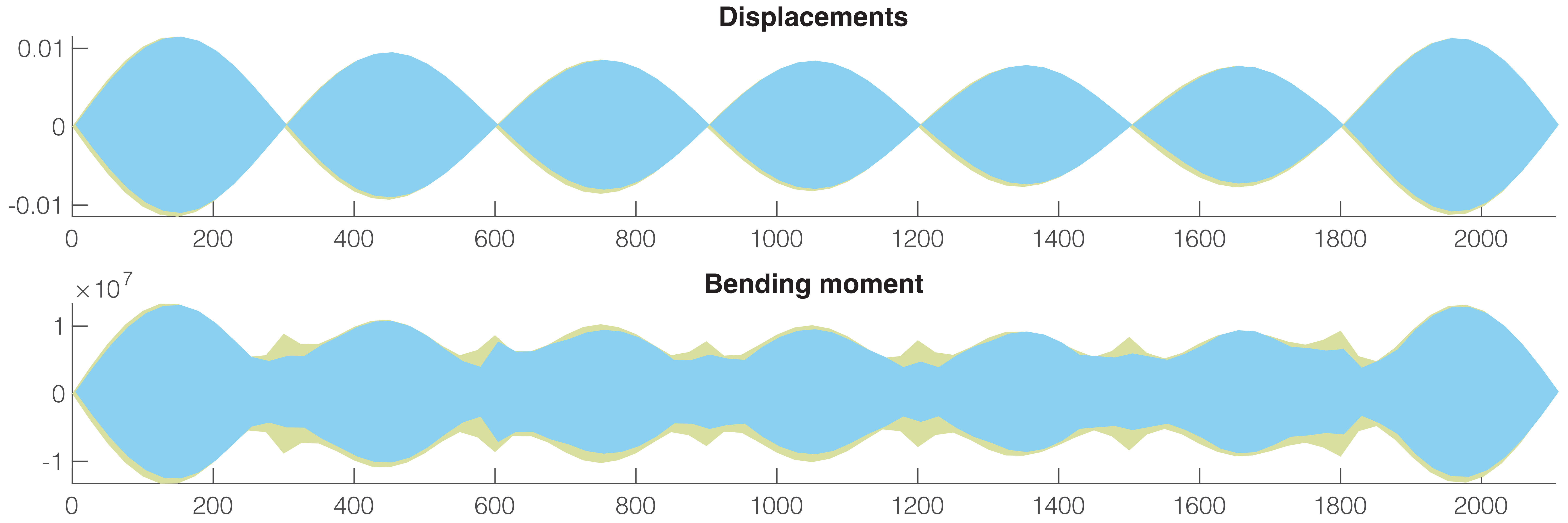
Comb. 1	**Comb. 2**
-0.16	-0.92
-0.45	1.00
1.00	-0.50
-0.04	-0.47
0.31	-0.08
-0.38	0.05
-0.14	-0.05

Combination of the first 7 PSWLs



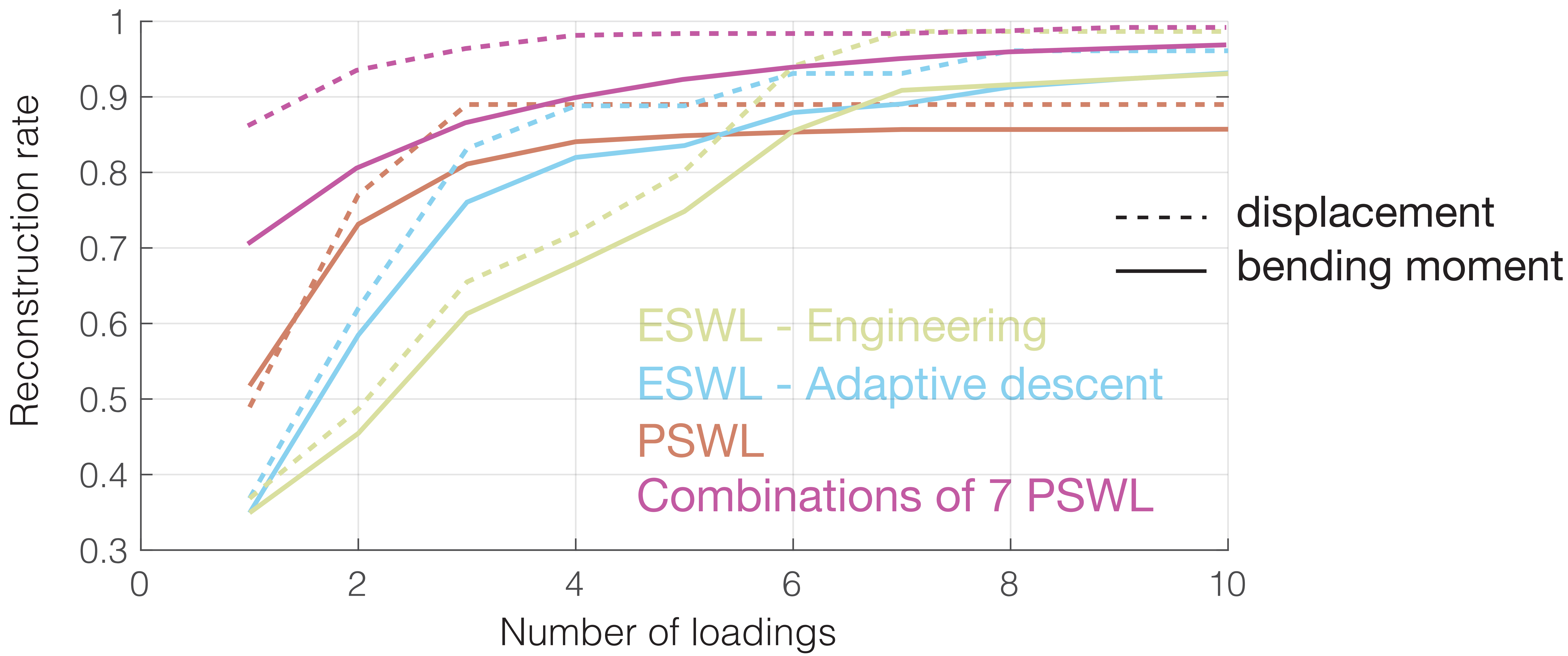
Comb. 1	Comb. 2	Comb. 3
-0.16	-0.92	-0.05
-0.45	1.00	1.00
1.00	-0.50	0.18
-0.04	-0.47	0.16
0.31	-0.08	-0.10
-0.38	0.05	0.02
-0.14	-0.05	0.21

Combination of the first 7 PSWLs



Comb. 1	Comb. 2	Comb. 3	Comb. 4	…	Comb. 10
-0.16	-0.92	-0.05	0.60	…	…
-0.45	1.00	1.00	0.77		
1.00	-0.50	0.18	0.75		
-0.04	-0.47	0.16	0.44		
0.31	-0.08	-0.10	1.00		
-0.38	0.05	0.02	0.16		
-0.14	-0.05	0.21	0.16	…	…

Principal static wind loads



Advantages :

- provide to client / design engineers a minimum number of load distributions that are realistic
- provide a number of combination coefficients
- simple and efficient (no over-estimation required)

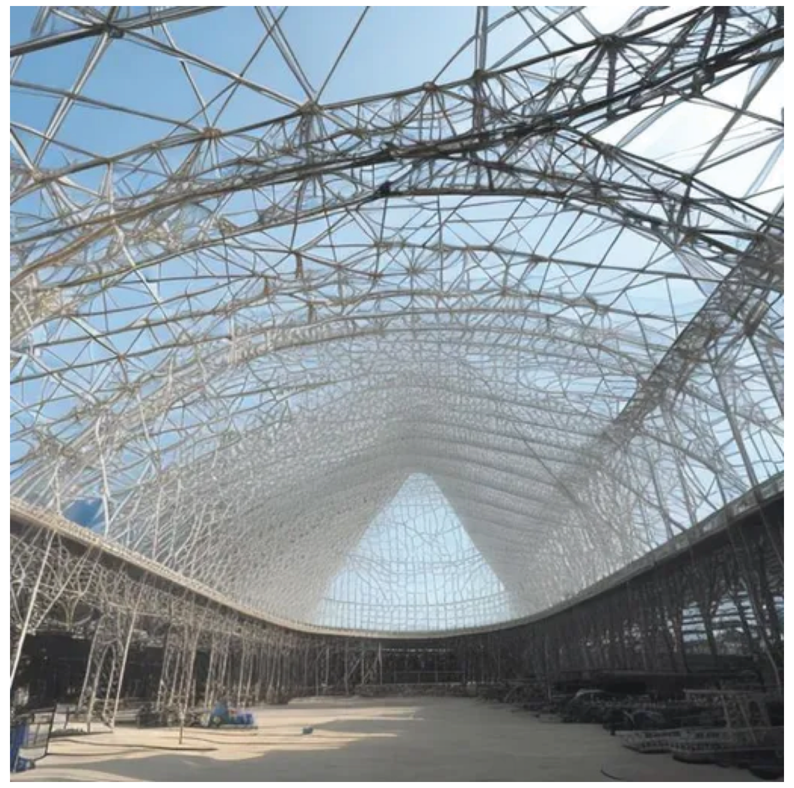
Future Challenges and Conclusions

Challenges : Large roofs, Silos, Cooling tower, Bridges, …

- Non-Symmetric envelopes
- Nonlinear responses, $\mathbf{z}(t) = \mathbf{A}\mathbf{x}(t)$
- Design/Extreme values
- Several wind incidences

See beyond buffeting

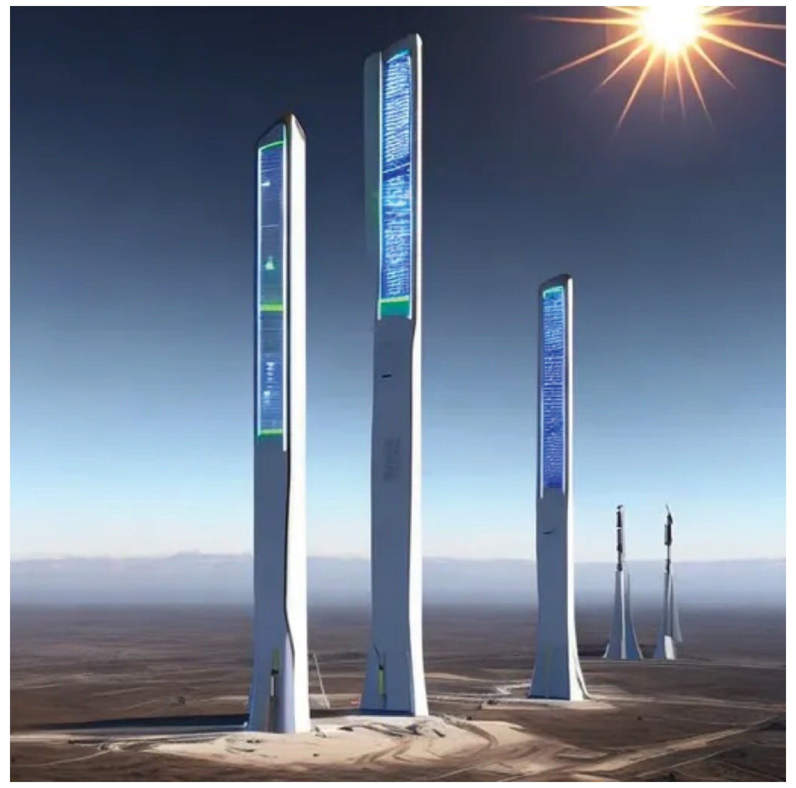
Traditional « engineering solutions » (vs. AI …)









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Editors
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Illustrations
OpenArt

Envelope Reconstruction with Equivalent Wind Loads

Vincent Denoël

LIÈGE université

Backup slides

$$M' = T \quad ; \quad M'' = p$$