Reliability-based calibration of partial factors for the future evolution of EN 1990 for wind actions

CEN/TC250/WG7 – Delft, The Netherlands, February 17, 2015

Thunderstorm monitoring, statistics and loading of structures

Giovanni Solari

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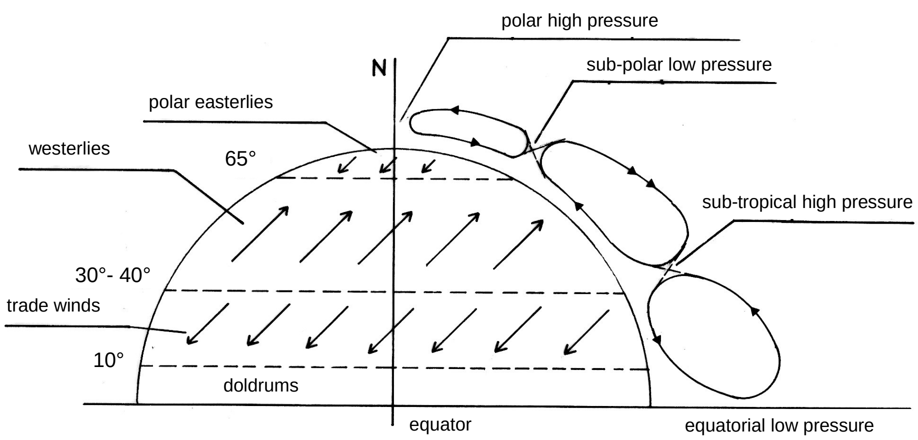
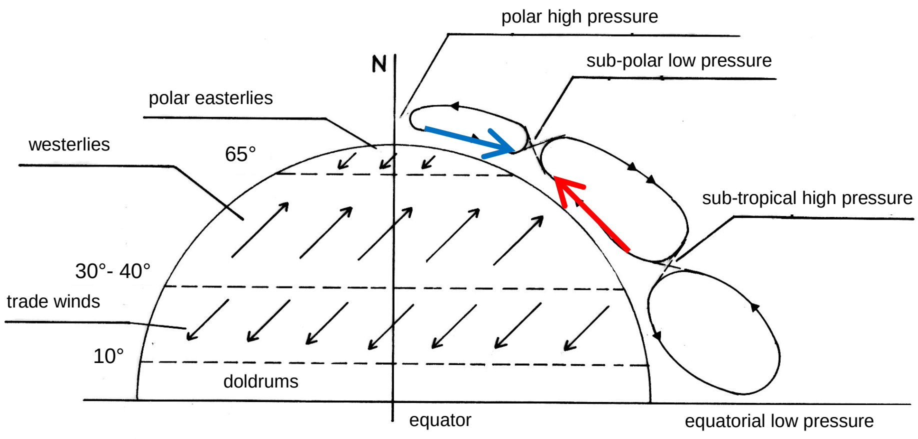
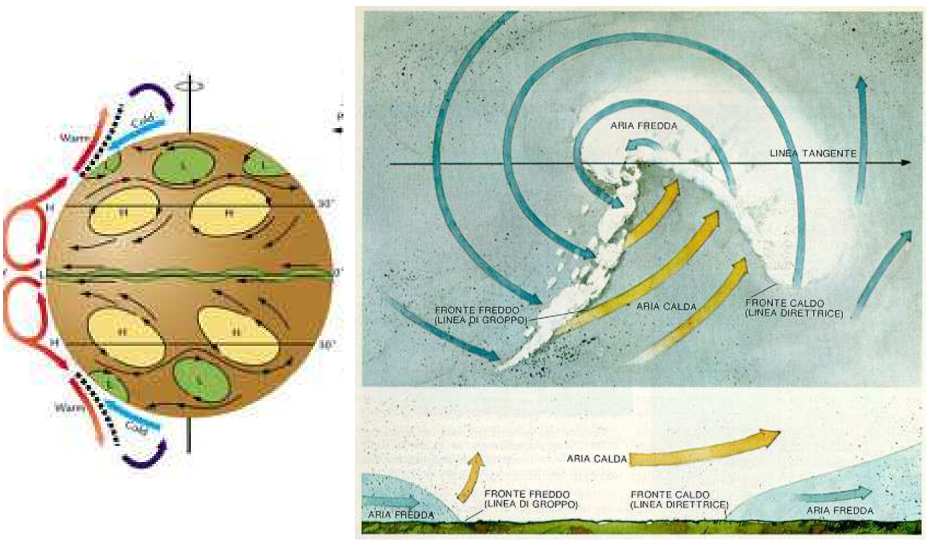
WinDyn



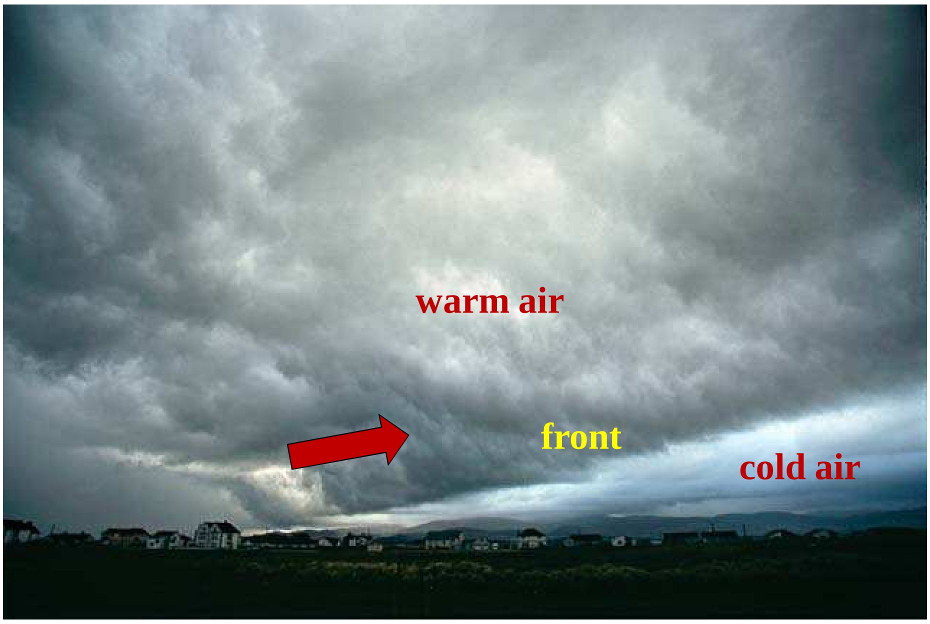
Farrel three-cellular circulation (1856)



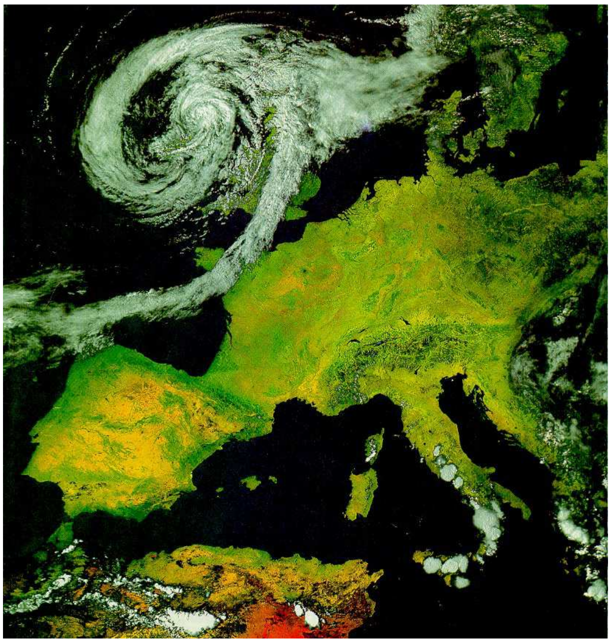
Farrel three-cellular circulation (1856)



Bjerknes and Solberg cyclogenetic model (1921)

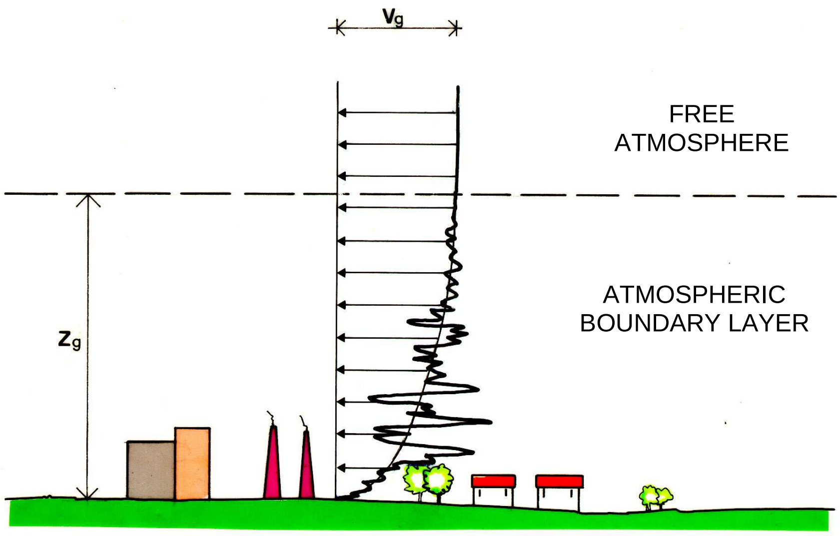


Gust front, Bjerknes and Solberg (1921)

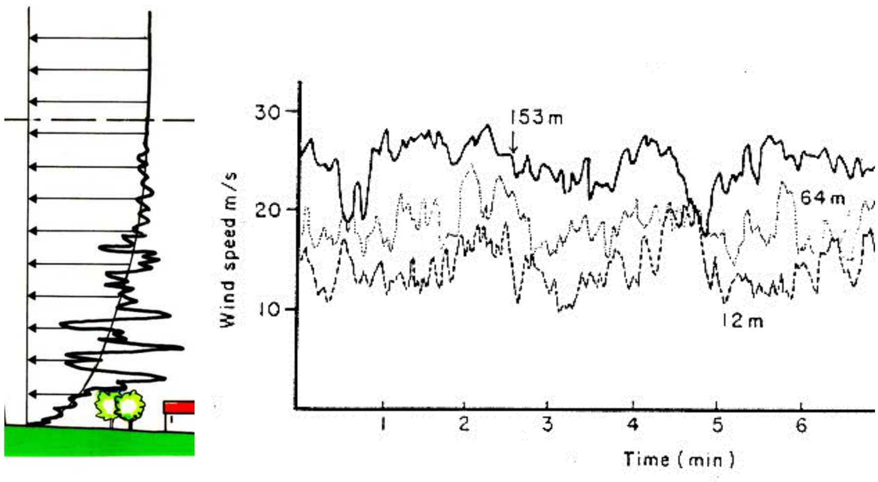


Satellite image of an extra-tropical cyclone

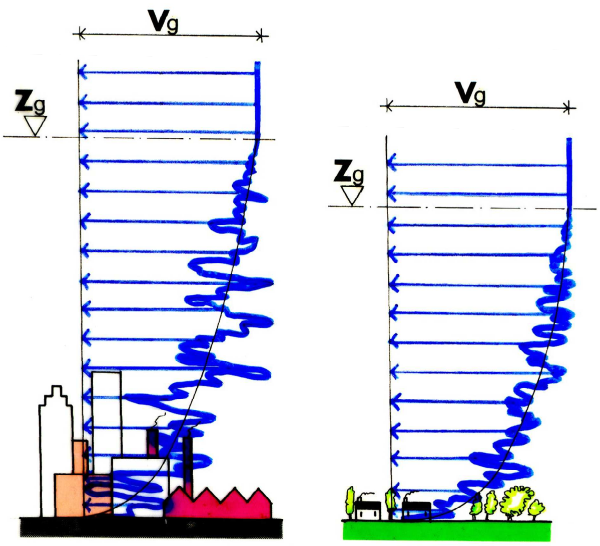
Atmospheric Boundary Layer



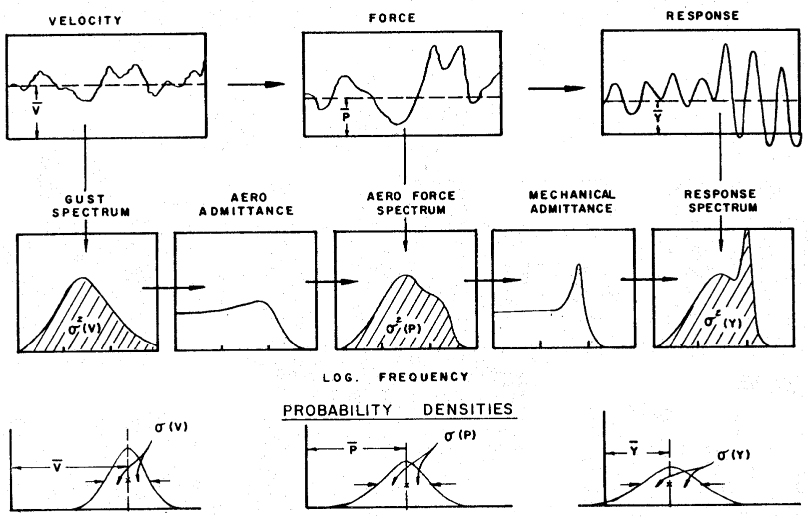
Atmospheric Boundary Layer



Atmospheric Boundary Layer



Extra-tropical cyclone



Wind Loading Chain, Davenport (1961)

Wind loading on structures

- Gust factor technique (ISO)
- Dynamic coefficient method (EC1)

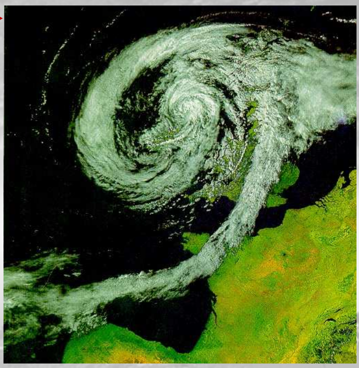
MIXED CLIMATE

Climatological condition in which several wind phenomena of different nature occur (Gomes & Vickery 1977/1978):

MIXED CLIMATE

Climatological condition in which several wind phenomena of different nature occur (Gomes & Vickery 1977/1978):

- **Extra-tropical cyclones**



MIXED CLIMATE

Climatological condition in which several wind phenomena of different nature occur (Gomes & Vickery 1977/1978):

- **Extra-tropical cyclones**
- **Tropical cyclones**

MIXED CLIMATE

Climatological condition in which several wind phenomena of different nature occur (Gomes & Vickery 1977/1978):

- Extra-tropical cyclones
- Tropical cyclones
- **Tornadoes**

MIXED CLIMATE

Climatological condition in which several wind phenomena of different nature occur (Gomes & Vickery 1977/1978):

- Extra-tropical cyclones
- Tropical cyclones
- Tornadoes
- **Downslope winds**

MIXED CLIMATE

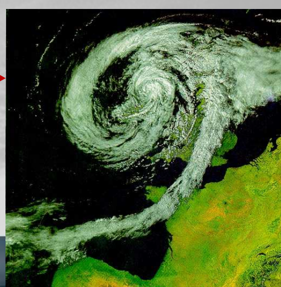
Climatological condition in which several wind phenomena of different nature occur (Gomes & Vickery 1977/1978):

- Extra-tropical depressions
- Tropical cyclones
- Tornadoes
- Downslope winds
- Thunderstorms

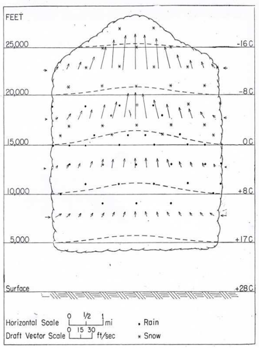
MIXED CLIMATE

Climatological condition in which several wind phenomena of different nature occur (Gomes & Vickery 1977/1978):

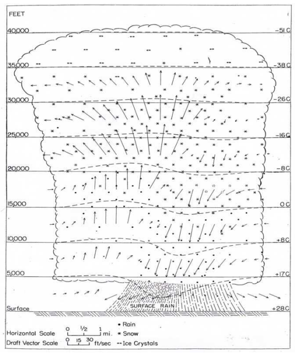
- Extra-tropical cyclones
- Tropical cyclones
- Tornadoes
- Downslope winds
- Thunderstorms



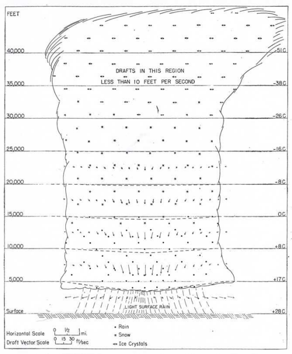
THUNDERSTORMS



Cumulus stage



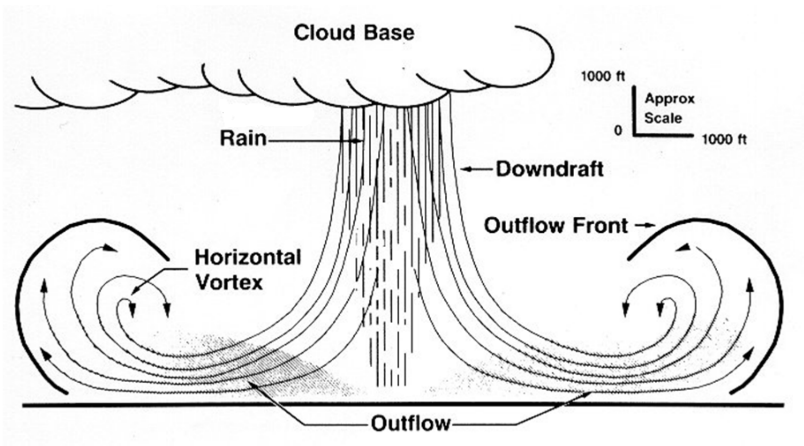
Mature stage



Dissipative stage

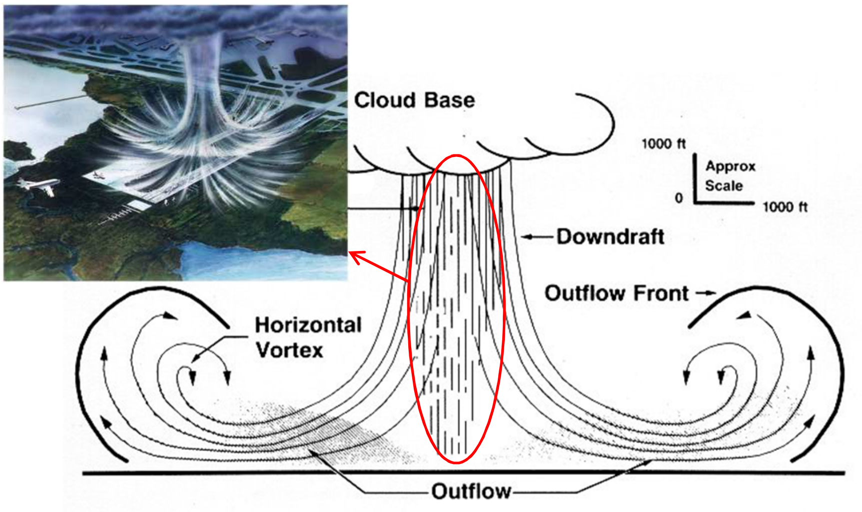
Thunderstorm Project, Byers and Braham (1949)

THUNDERSTORMS



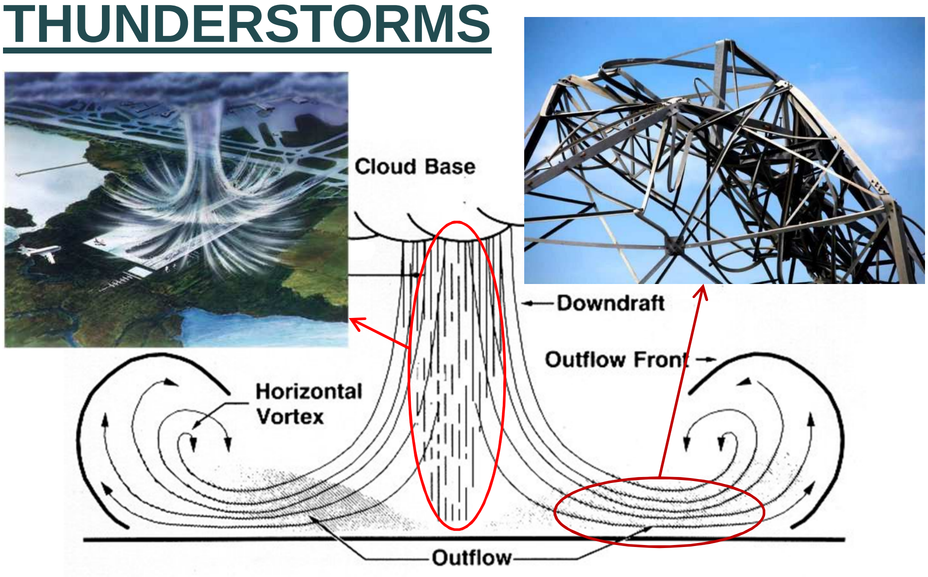
Downburst, Fujita (1981, 1985, 1990)

THUNDERSTORMS



Downburst, Fujita (1981, 1985, 1990)

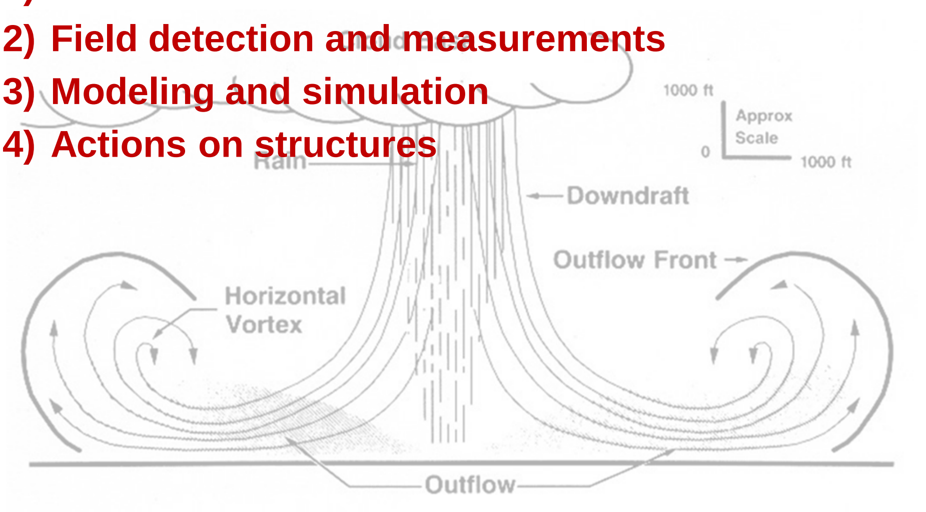
THUNDERSTORMS



Downburst, Fujita (1981, 1985, 1990)

THUNDERSTORMS

1) **Wind statistics and climate**
2) **Field detection and measurements**
3) **Modeling and simulation**
4) **Actions on structures**



THUNDERSTORMS

In spite of this impressive amount of research, there is not yet a model of thunderstorms and their actions on structures like that for cyclones.

1) The complexity of this phenomenon makes it difficult to formulate physically realistic and simple models.
2) Its short duration and small size make very few measured data available.
3) There is still a great gap between the research in wind engineering and atmospheric sciences.

THUNDERSTORMS

Wind actions on structures are still mostly determined by the model for cyclones developed half a century ago, at the most taking thunderstorms into account in the statistical evaluation of wind speed.

This is not enough, because cyclones and thunderstorms are different phenomena that need separate assessments.

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Thunderstorm monitoring, statistics and loading of structures

Wind monitoring

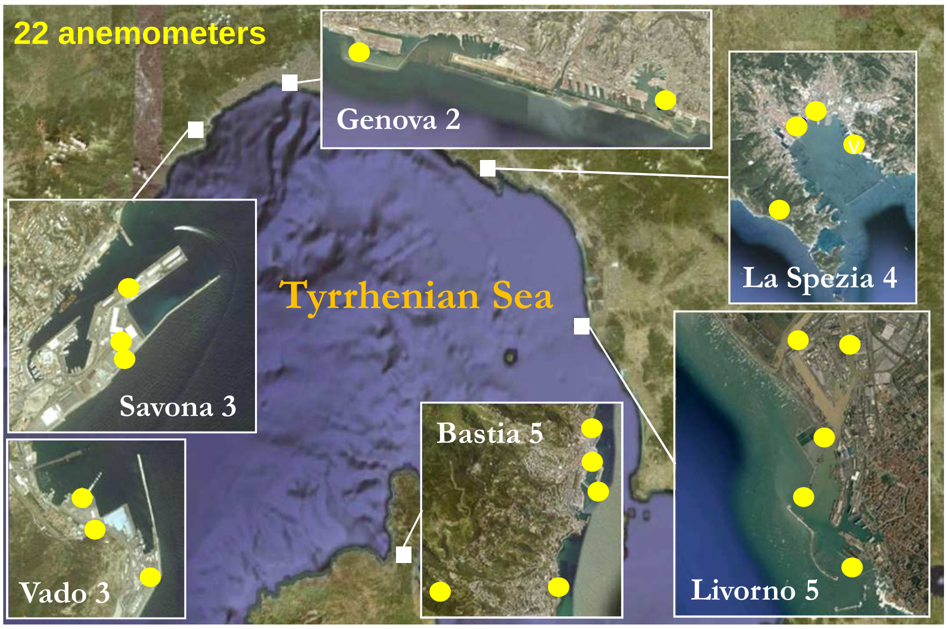
“Wind & Ports” Project (2009-2012)

Aims of the project

1) Wind monitoring network and dataset
2) Wind field modelling and simulation
3) Statistical analysis of wind climate
4) Medium-term wind forecasting
5) Short-term wind forecasting

Solari at al., JWEIA, 2012.

“Wind & Ports” Project (2009-2012)

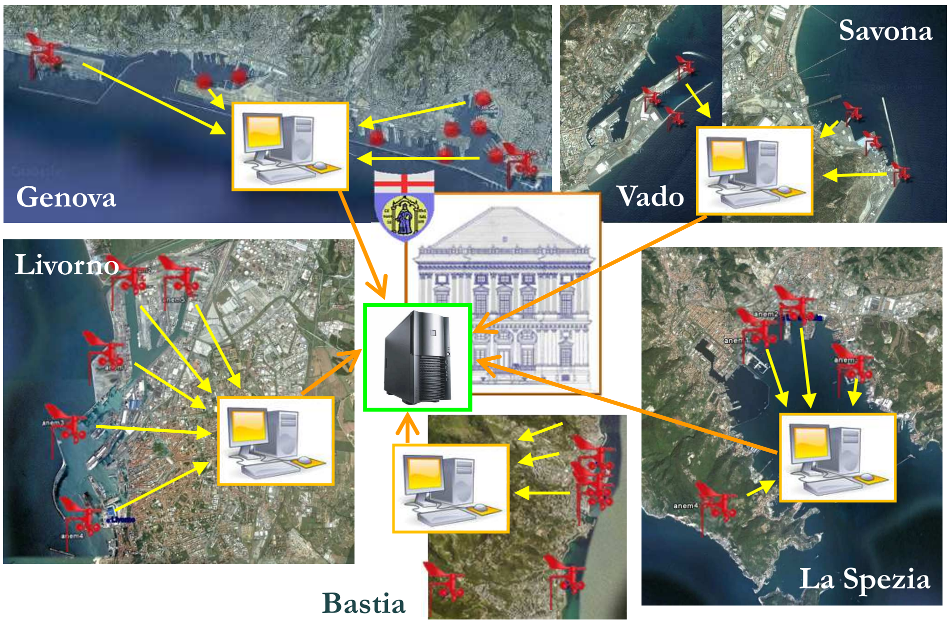


“Wind & Ports” Project (2009-2012)

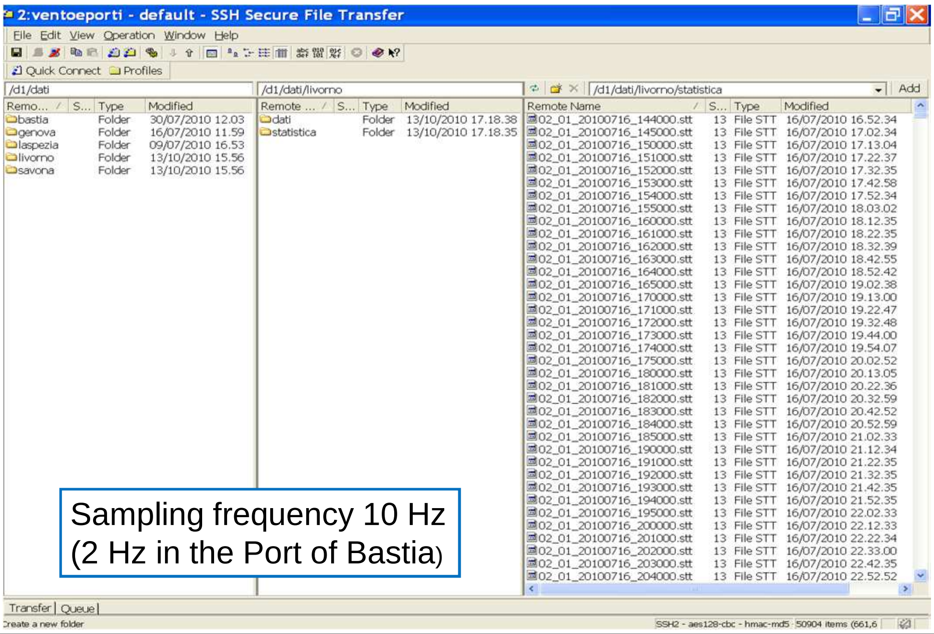
“Wind & Ports” Project monitoring network

“Wind & Ports” Project monitoring network

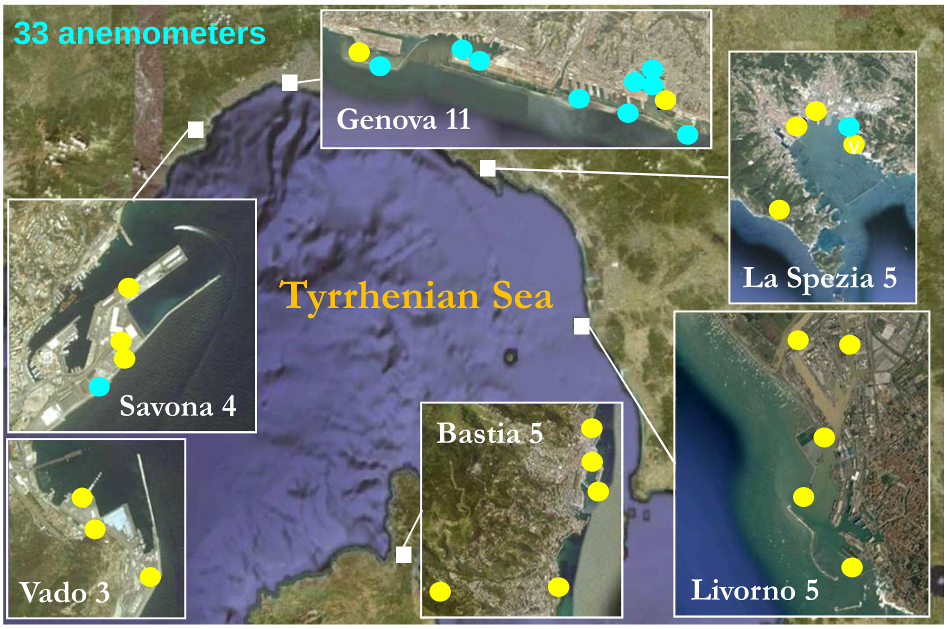
“Wind & Ports” Project (2009-2012)



“Wind & Ports” Project (2009-2012)



“Wind & Ports” Project (2013-2014)



La Cooperazione al cuore del Mediterraneo

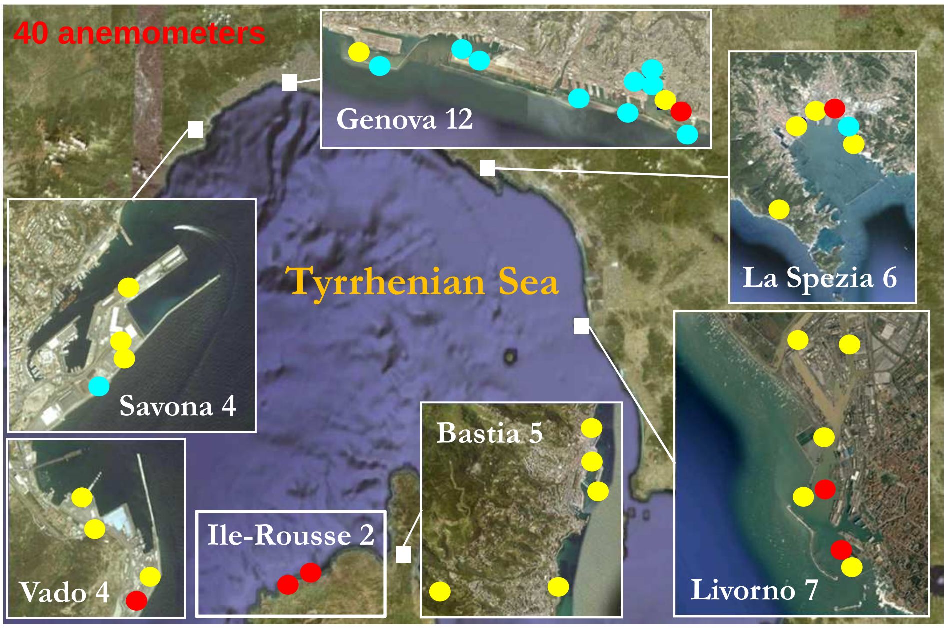
MARITTIMO - IT FR - MARITIME
TOSCANA - LIGURIA - SARDEGNA - CORSE

Wind, Ports & Sea Project (2013-2015)

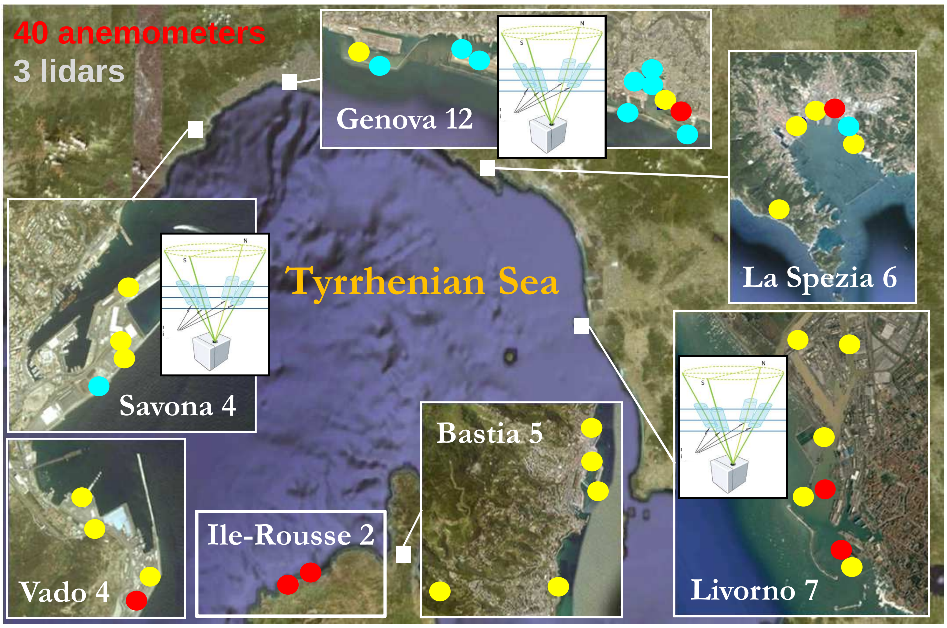
1) Strengthening the monitoring network
2) Detecting sea waves by sismometers
3) Improving existing wind forecasting
4) Forecasting sea waves

Burlando et al., Proc., 6th CWE, Hamburg, Germany, 2014
Burlando et al., Proc., 14th ICWE, Porto Alegre, Brasil, 2015

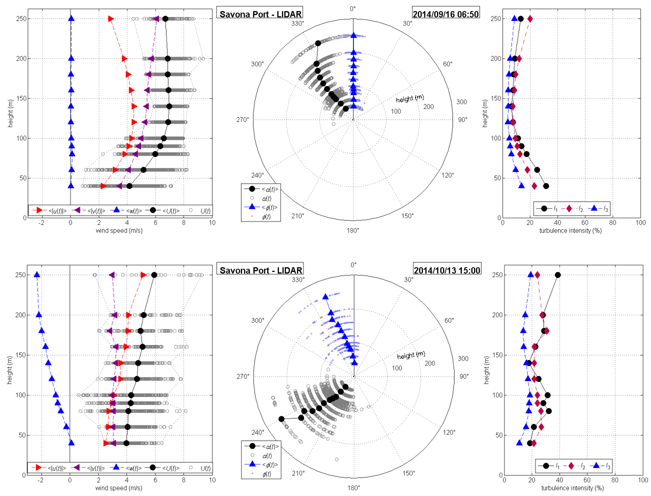
"Wind, Ports & Sea" Project (2013-2015)



“Wind, Ports & Sea” Project (2013-2015)



LiDAR, Port of Savona



Burlando et al., Proc., 14th ICWE, Porto Alegre, Brasil, 2015

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Thunderstorm monitoring, statistics and loading of structures

Wind classification

WIND PHENOMENA

1) Extra-tropical depressions (D)
   stationary & Gaussian phenomena

2) Thunderstorms (T)
   non-stationary & non-Gaussian phenomena

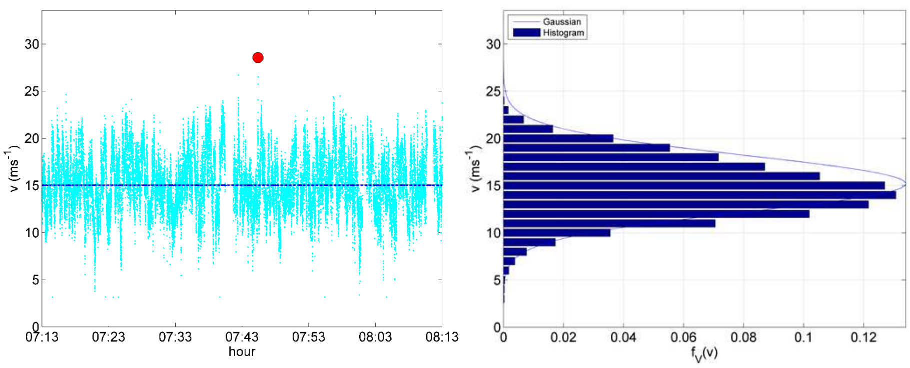
WIND PHENOMENA

1) Extra-tropical depressions (D)
   stationary & Gaussian phenomena

2) Thunderstorms (T)
   non-stationary & non-Gaussian phenomena

3) Intermediate events (F)
   stationary & non-Gaussian phenomena

EXTRA-TROPICAL DEPRESSIONS
Stationary & Gaussian

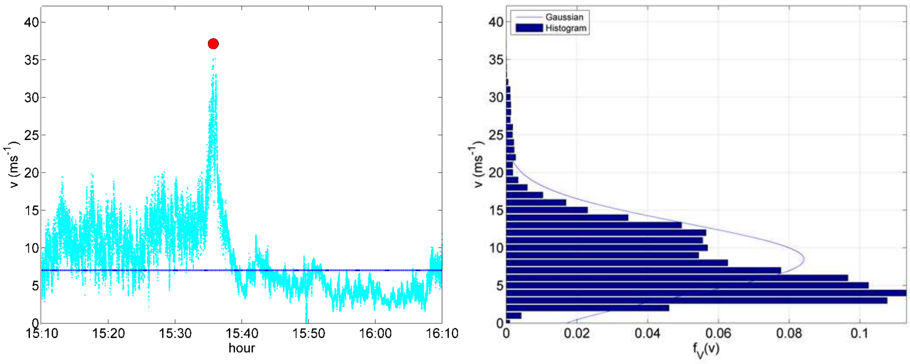


$V_{p60} = 22.46 \text{ m/s}; \quad V_{m60} = 15.03 \text{ m/s}; \quad G_{60} = 1.49$

$\text{skewness} = 0.06; \quad \text{excess kurtosis} = 0.08$

THUNDERSTORMS

Non-stationary & non-Gaussian

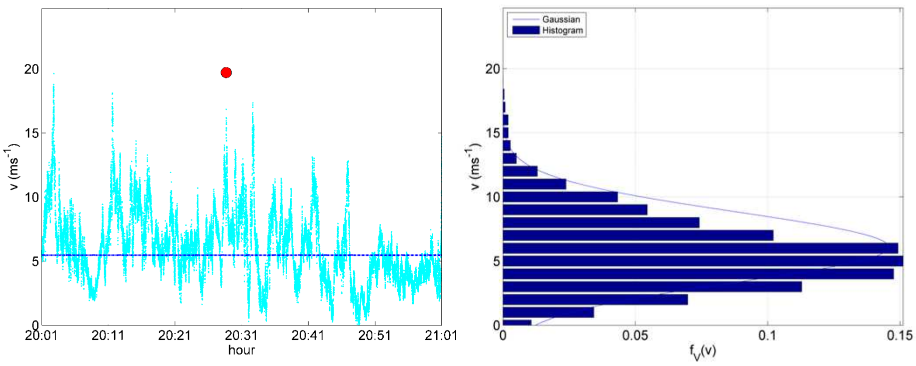


$$V_{p60} = 33.36\,\mathrm{m/s}; \quad V_{m60} = 7.33\,\mathrm{m/s}; \quad G_{60} = 4.55$$

$$\text{skewness} = 1.20; \quad \text{excess kurtosis} = 2.60$$

INTERMEDIATE EVENTS

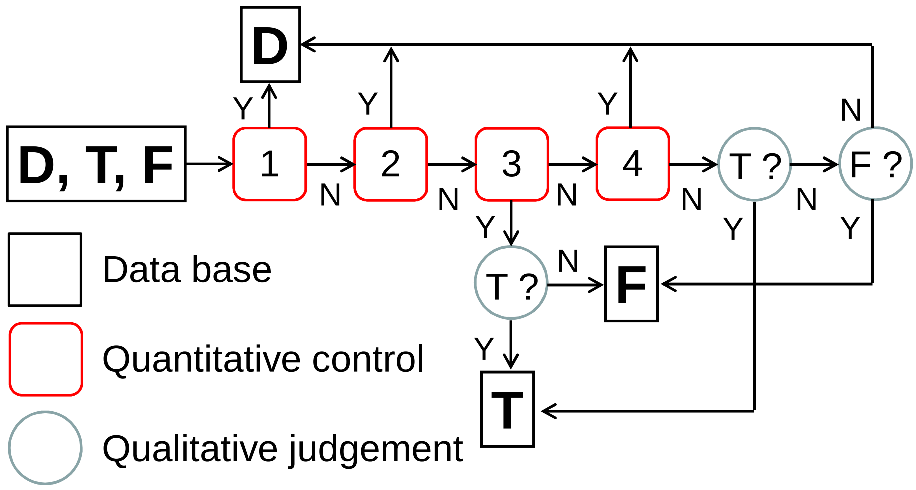
Stationary & non-Gaussian



$$V_{p60} = 15.68\,\mathrm{m/s}; \quad V_{m60} = 5.51\,\mathrm{m/s}; \quad G_{60} = 2.85$$

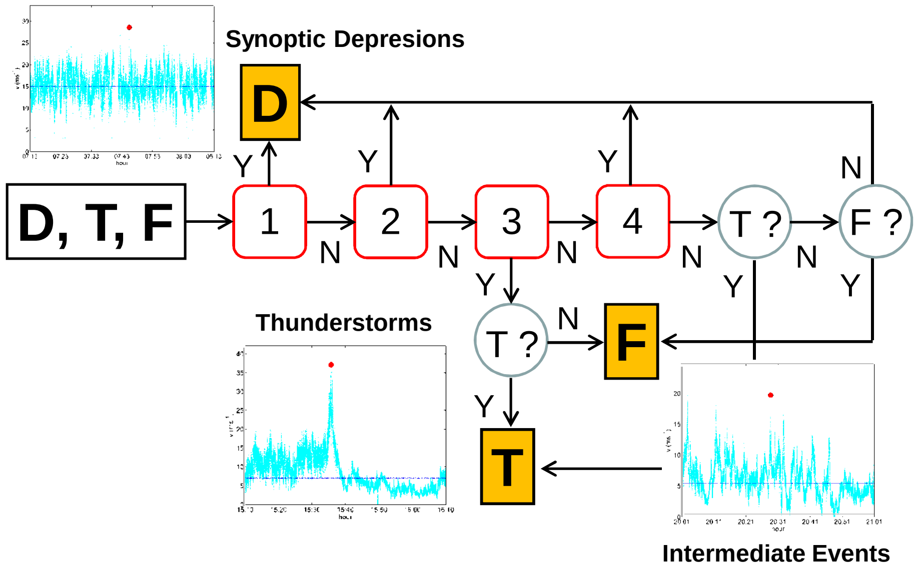
$$\text{skewness} = 0.63; \quad \text{excess kurtosis} = 0.61$$

SEMI-AUTOMATED EXTRACTION AND CLASSIFICATION ALGORITHM



De Gaetano et al., JWEIA, 2014.

SEMI-AUTOMATED EXTRACTION AND CLASSIFICATION ALGORITHM



SEMI-AUTOMATED EXTRACTION AND CLASSIFICATION ALGORITHM

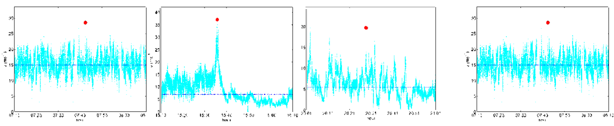
U_{p10}, U_{m10}; storms

$U_{p10}>U^*_{p10}$; U_{m10}; I_{10}, G_{10}, γ_{10}, κ_{10}; …

$U_{m10}>U^*_{m10}$; U_{p10}; I_{10}, G_{10}, γ_{10}, κ_{10}; …

U_{p10} **D** | U_{p10} **T** | U_{p10} **F** | U_{m10} **D** | U_{m10} **T** | U_{m10} **F**

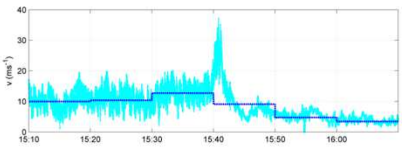
max U_{p10} **D** | max U_{p10} **T** | max U_{p10} **F** | max U_{m10} **D**

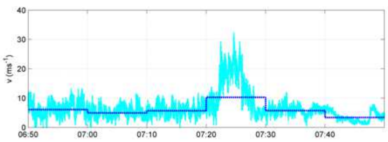


Independence criterion

3 days between depressions
4 hours between thunderstorms
1 day between intermediate events

THUNDERSTORMS (2011-2012)

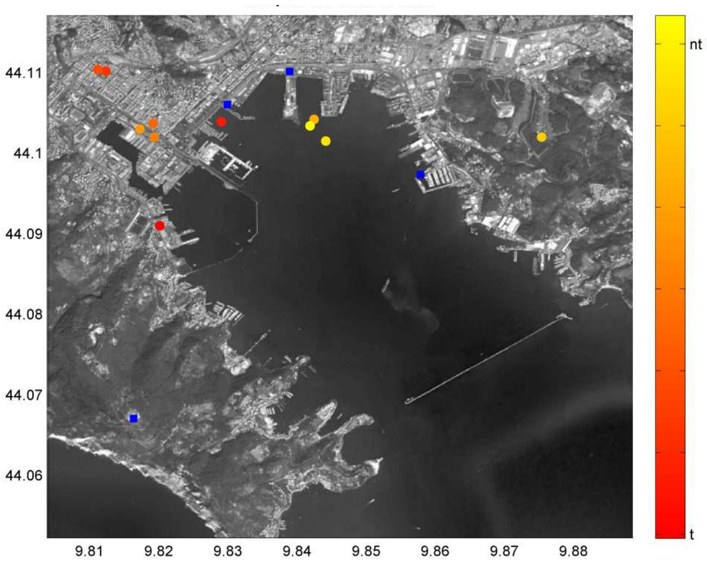




Port	Number of thunderstorm events	Anemometer Number	Number of thunderstorm records
Genoa	21	1	12
		2	11
La Spezia	16	2	8
		3	14
Livorno	27	1	12
		2	7
		3	12
		4	5
		5	12
All ports	64	-	93

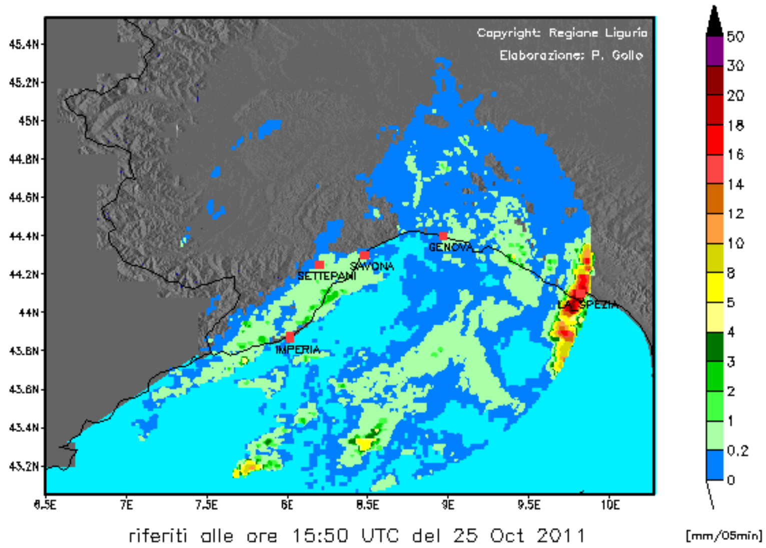
Solari et al., Wind & Structures, 2014, submitted.

Port of La Spezia – Thunderstorm October 25, 2011



CESI network lightning map

Port of La Spezia – Thunderstorm October 25, 2011



Doppler radar rainfall image

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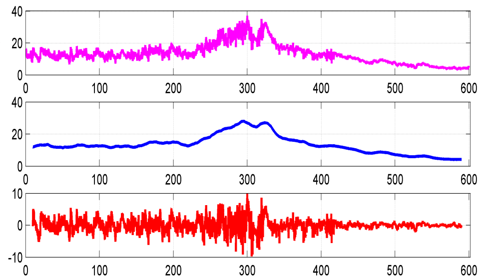
Thunderstorm modelling

THUNDERSTORM DECOMPOSITION

$\boxed{v(t) = \bar{v}(t) + v'(t)}$

$\bar{v}(t)$

$v'(t)$



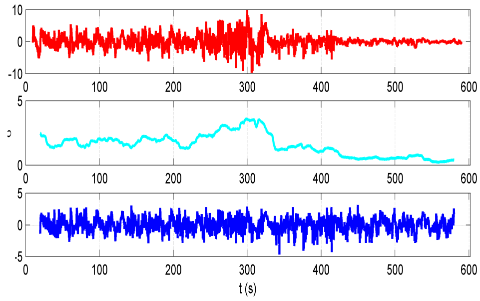
Moving average period T = 30 s

THUNDERSTORM DECOMPOSITION

$$\boxed{v'(t) = \sigma_v(t) \cdot \tilde{v}'(t)}$$

$$\sigma_v(t)$$

$$\tilde{v}'(t)$$



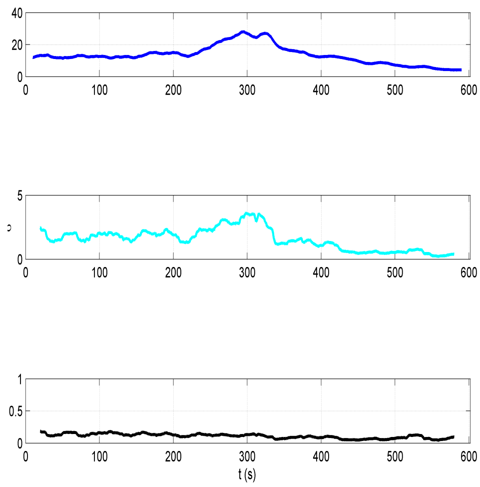
Moving average period T = 30 s

THUNDERSTORM DECOMPOSITION

$$\bar{v}(t)$$

$$\sigma_v(t)$$

$$\boxed{I_v(t) = \frac{\sigma_v(t)}{\bar{v}(t)}}$$



THUNDERSTORM DECOMPOSITION

$$\boxed{v(t) = \bar{v}(t)\left[1 + I_v(t)\cdot\tilde{v}'(t)\right]}$$

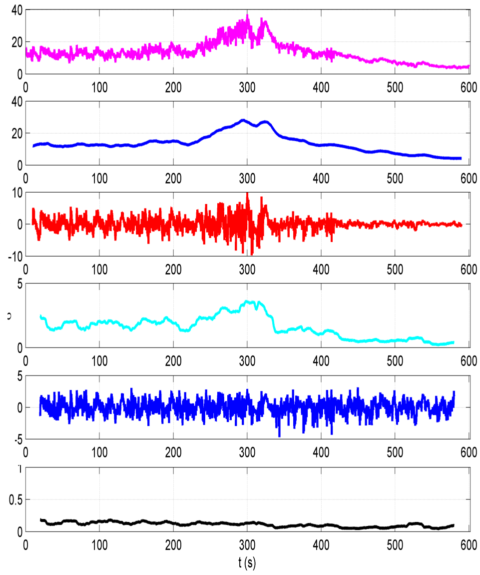
$\bar{v}(t)$ →

$v'(t)$ →

$\sigma_v(t)$ →

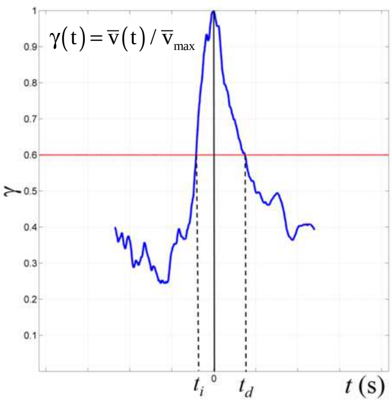
$\tilde{v}'(t)$ →

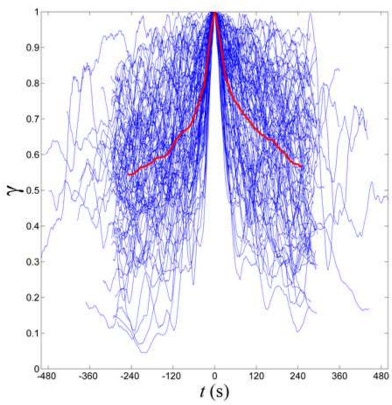
$I_v(t)$ →



THUNDERSTORM DECOMPOSITION

$$\boxed{v(t) = \bar{v}(t)\left[1 + I_v(t)\cdot\tilde{v}'(t)\right]}$$

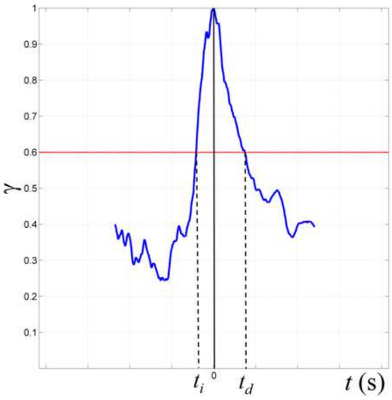




Thunderstorm duration

THUNDERSTORM DECOMPOSITION

$$\boxed{v(t)=\bar{v}(t)\left[1+I_v(t)\cdot\tilde{v}'(t)\right]}$$



Increasing time period t_i
Mean value 116 s
Minimum value 22 s

Decreasing time period t_d
Mean value 132 s
Minimum value 27 s

Total duration t_t
Mean value 248 s
Minimum value 57 s

Thunderstorm duration

THUNDERSTORM DECOMPOSITION

$$\boxed{v(t)=\bar{v}(t)\left[1+I_v(t)\cdot\tilde{v}'(t)\right]}$$

Average turbulence intensity

Port	Anemometer number	Thunderstorms
Genoa	1	0.12
	2	0.12
Livorno	1	0.10
	2	0.16
	3	0.08
	4	0.07
	5	0.13
La Spezia	2	0.17
	3	0.14
All ports		0.12

THUNDERSTORM DECOMPOSITION

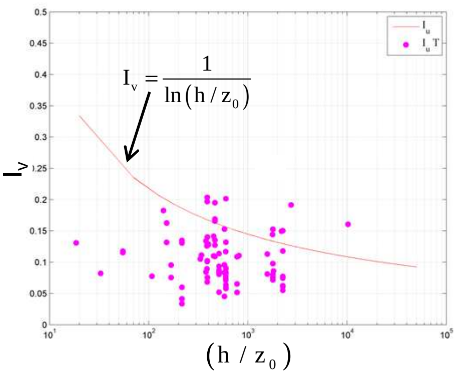
$$\boxed{v(t)=\overline{v}(t)\left[1+I_v(t)\cdot\tilde{v}'(t)\right]}$$

Average turbulence intensity

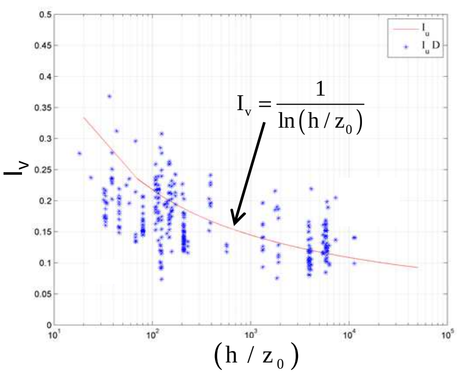
Port	Anemometer number	Thunderstorms	Synoptic
Genoa	1	0.12	0.18
	2	0.12	0.18
Livorno	1	0.10	0.16
	2	0.16	0.20
	3	0.08	0.14
	4	0.07	0.14
	5	0.13	0.18
La Spezia	2	0.17	0.23
	3	0.14	0.21
All ports		0.12	0.18

THUNDERSTORM DECOMPOSITION

$$\boxed{v(t)=\overline{v}(t)\left[1+I_v(t)\cdot\tilde{v}'(t)\right]}$$



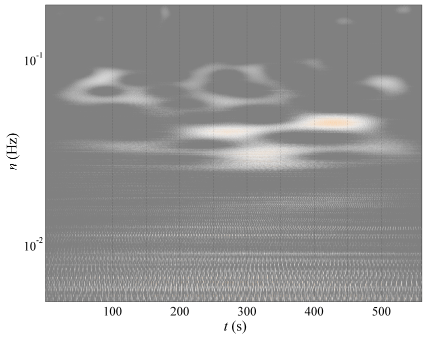
Thunderstorms



Synoptic events

THUNDERSTORM DECOMPOSITION

$$\boxed{v(t)=\bar{v}(t)\left[1+I_v(t)\cdot\tilde{v}'(t)\right]}$$



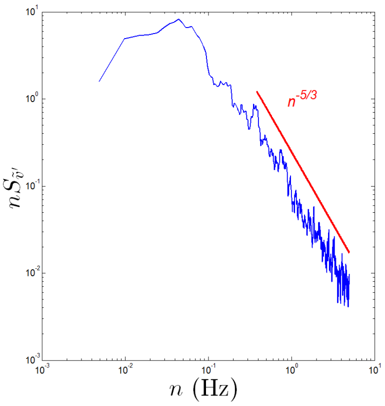
Reduced turbulence fluctuation

Mean value ~ 0.0
Standard deviation ~ 1.0
Skewness ~ 0.0
Kurtosis ~ 2.8

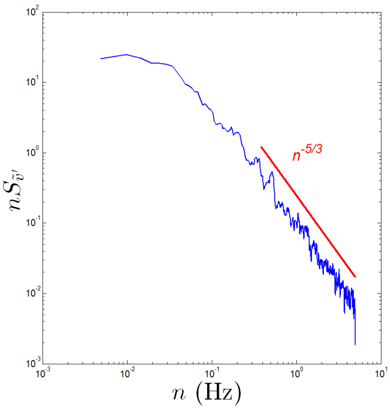
Reduced stochastic stationary Gaussian process

THUNDERSTORM DECOMPOSITION

$$\boxed{v(t)=\bar{v}(t)\left[1+I_v(t)\cdot\tilde{v}'(t)\right]}$$



Thunderstorms



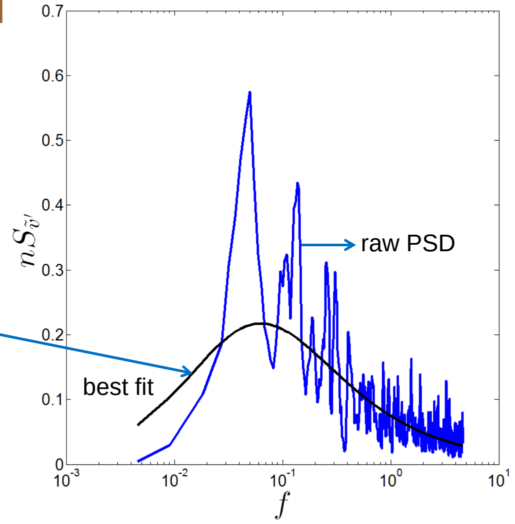
Synoptic events

THUNDERSTORM DECOMPOSITION

$$v(t)=\bar{v}(t)\left[1+I_v(t)\cdot\tilde{v}'(t)\right]$$

Solari & Piccardo, PEM, 2001

$$nS(n)=\frac{6.868nL_v/\bar{v}}{(1+10.302nL_v/\bar{v})^{5/3}}$$



Integral length scale

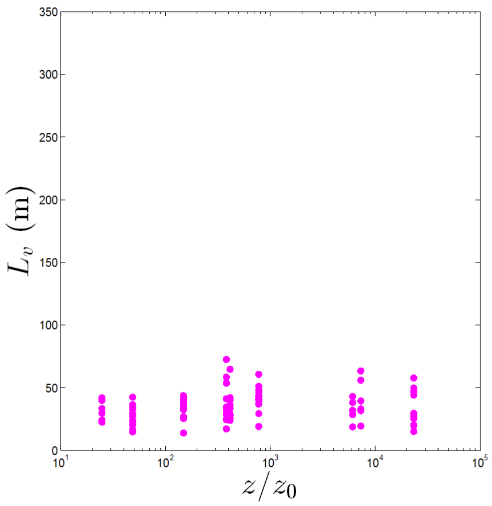
Thunderstorms L_v = 20-40 m
Synoptic events L_v = 80-150 m

THUNDERSTORM DECOMPOSITION

$$v(t)=\bar{v}(t)\left[1+I_v(t)\cdot\tilde{v}'(t)\right]$$

Solari & Piccardo, 2001

$$nS(n)=\frac{6.868nL_v/\bar{v}}{(1+10.302nL_v/\bar{v})^{5/3}}$$



Integral length scale

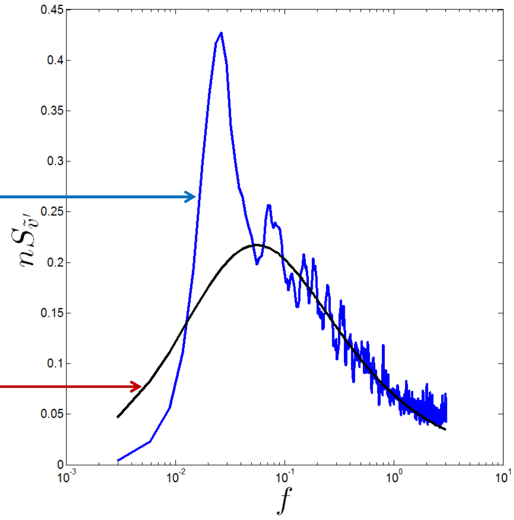
Thunderstorms L_v = 20-40 m
Synoptic events L_v = 80-150 m

THUNDERSTORM DECOMPOSITION

$$\boxed{v(t) = \bar{v}(t)\left[1 + I_v(t) \cdot \tilde{v}'(t)\right]}$$

PSD averaged
over all thunderstorms,
all anemometers
and all ports

$$\boxed{nS_{\tilde{v}'}(n) = \frac{18f}{(1+27f)^{5/3}}}$$



Reliability-based calibration of partial factors for the future evolution of EN 1990 for wind actions

CEN/TC250/WG7 – Delft, The Netherlands, February 17, 2015

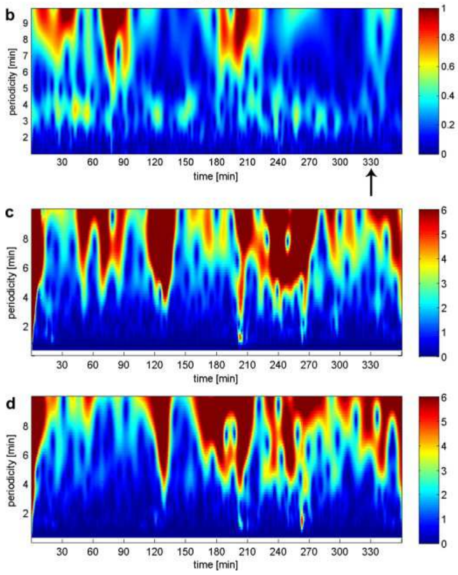
Thunderstorm monitoring, statistics
and loading of structures

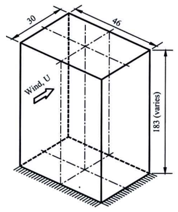
Thunderstorm response of structures

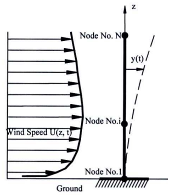
WinDyn

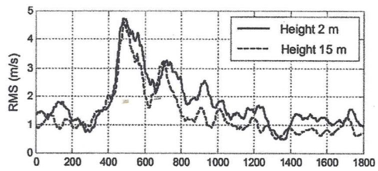
THUNDERSTORM-EXCITED RESPONSE
Non-stationary & non-Gaussian

- Hybrid deterministic/stochastic methods
- Time/frequency domain solutions
- Empirical mode decomposition
- Wavelet and Hilbert transforms
- Evolutionary spectral densities

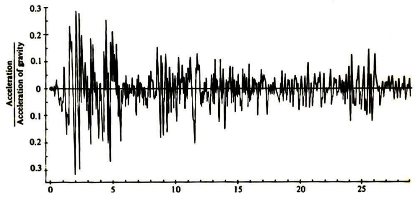




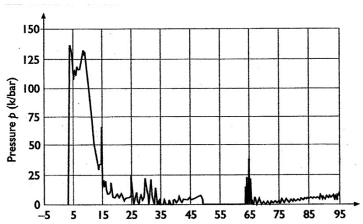




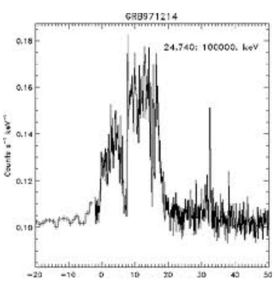
TRANSIENT PHENOMENA
Non-stationary & non-Gaussian



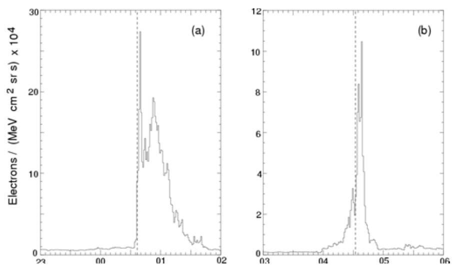
Earthquake



Impact

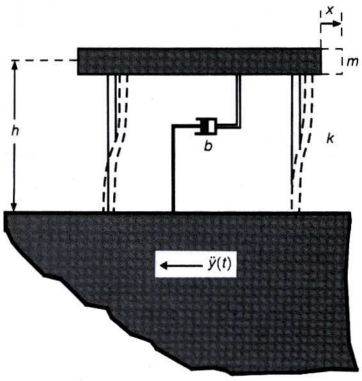


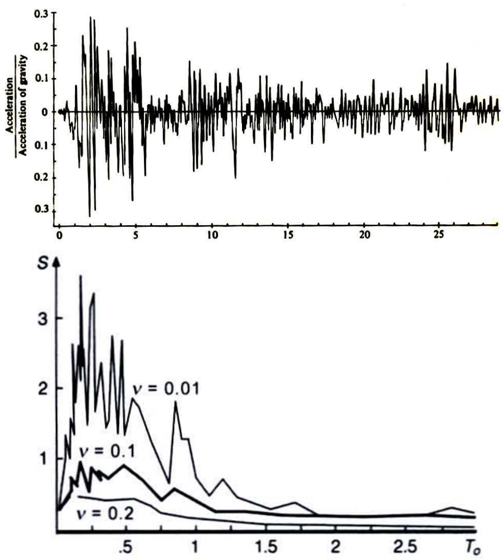
Blast



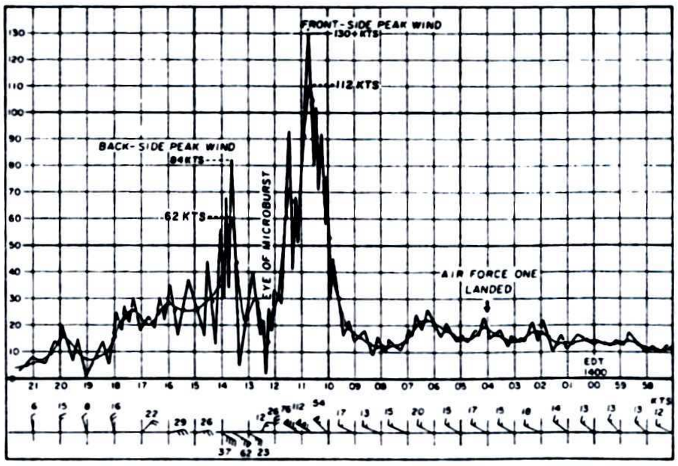
Shock-waves

EARTHQUAKES
Non-stationary & non-Gaussian





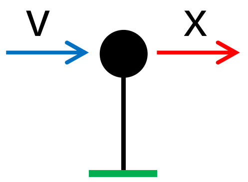
THUNDERSTORMS
Non-stationary & non-Gaussian



Solari, De Gaetano & Repetto (2013)
Thunderstorm response spectrum

Single-Degree-Of-Freedom system

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=f(t)=\frac{1}{2}\rho v^2(t)Ac_D$$



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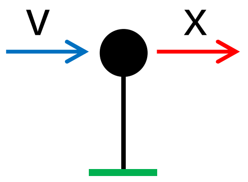


$u(t)=v(t)/\hat{v}_\tau$ = reduced wind velocity

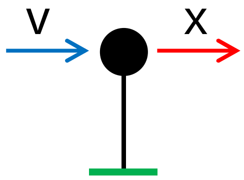
$\hat{v}_\tau$ = peak wind velocity over τ

$\hat{f}_\tau=0.5\rho\hat{v}^2Ac_D$ = peak wind loading

$d(t)=x(t)/\hat{x}_\tau$ = reduced displacement

$\hat{x}_\tau=\hat{f}_\tau/k$ = peak static displacement

Single-Degree-Of-Freedom system



$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=f(t)=\frac{1}{2}\rho v^2(t)Ac_D$$

$$\boxed{\ddot{d}(t)+2\xi\omega_0\dot{d}(t)+\omega_0^2 d(t)=\omega_0^2 u^2(t)}$$

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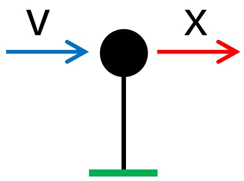

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=f(t)=\frac{1}{2}\rho v^2(t)Ac_D$$

$$\boxed{\ddot{d}(t)+2\xi\omega_0\dot{d}(t)+\omega_0^2 d(t)=\omega_0^2 u^2(t)}$$

THUNDERSTORM RESPONSE SPECTRUM

$$\boxed{S_d=d_{max}=\max\left[d(t)\right]}$$

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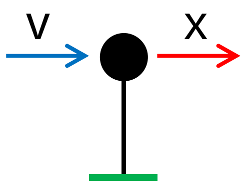


$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=f(t)=\frac{1}{2}\rho v^2(t)Ac_D$$

$$\ddot{d}(t)+2\xi\omega_0\dot{d}(t)+\omega_0^2 d(t)=\omega_0^2 u^2(t)$$

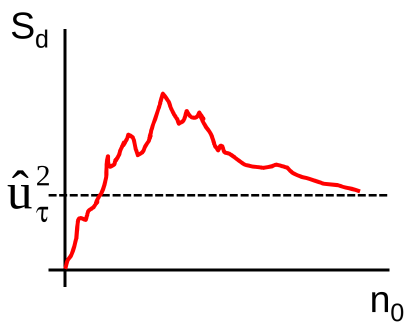
THUNDERSTORM RESPONSE SPECTRUM

$$\boxed{S_d = d_{max} = \max\left[d(t)\right]}$$

Maximum displacement $\boxed{x_{max} = \hat{x}_\tau \cdot S_d}$

Equivalent static force $\boxed{f_{eq} = \hat{f}_\tau \cdot S_d}$

THUNDERSTORM RESPONSE SPECTRUM

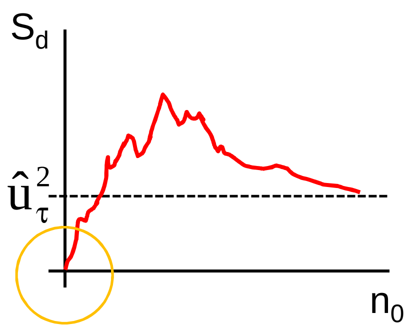


$\hat{u}_\tau = \dfrac{\hat{v}}{\hat{v}_\tau}$ = peak reduced wind velocity

$\hat{v} = \max\left[v(t)\right]$ = peak instantaneous wind velocity

$\hat{v}_\tau = \max\left[\langle v(t)\rangle_\tau\right]$ = peak wind velocity over τ

THUNDERSTORM RESPONSE SPECTRUM



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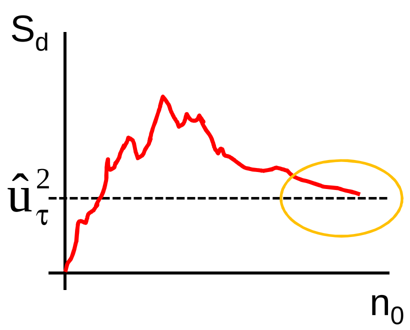

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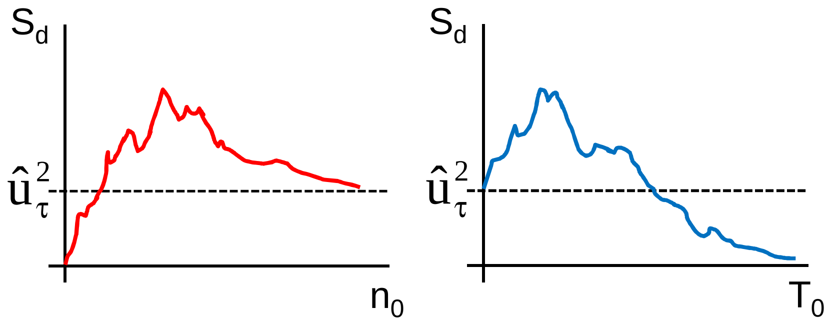
THUNDERSTORM RESPONSE SPECTRUM



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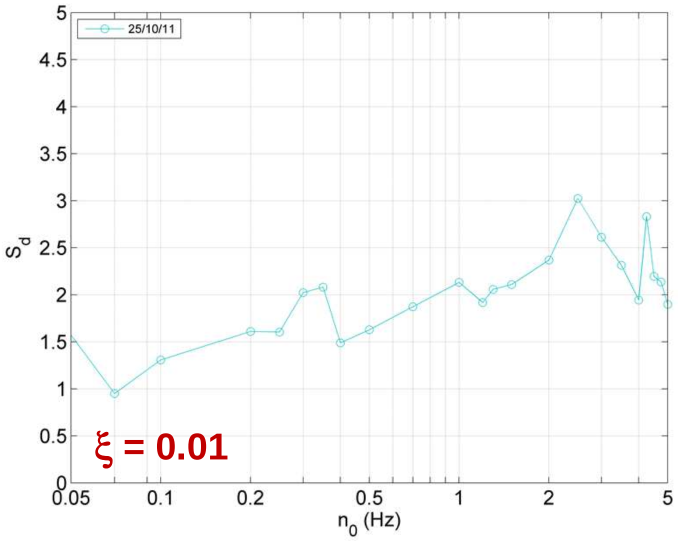
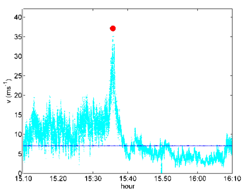
THUNDERSTORM RESPONSE SPECTRUM

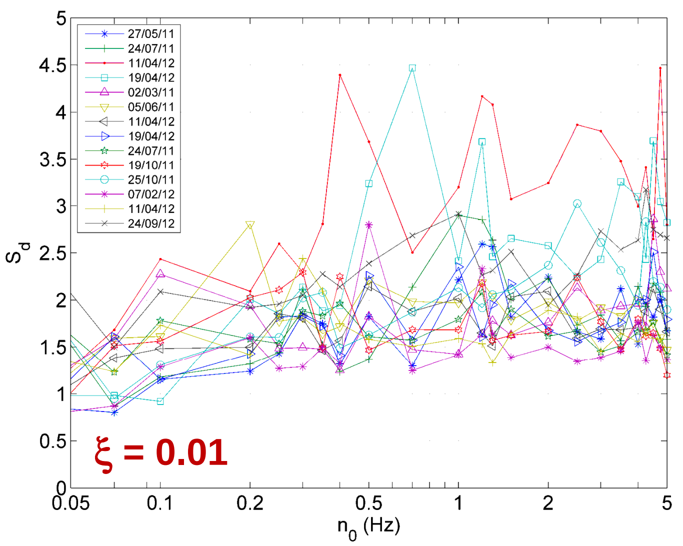
Port of La Spezia





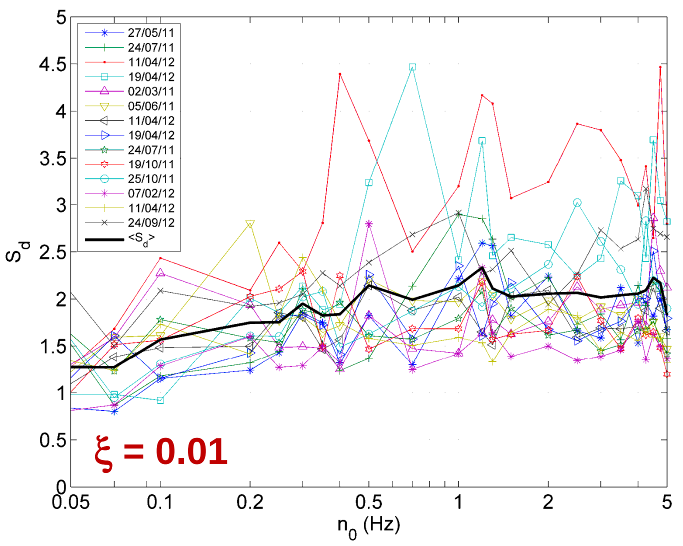
THUNDERSTORM RESPONSE SPECTRUM

Port of La Spezia



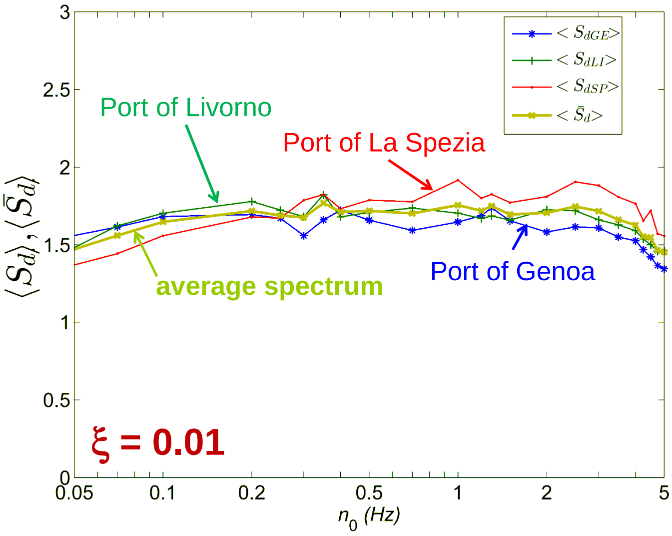
THUNDERSTORM RESPONSE SPECTRUM

Port of La Spezia



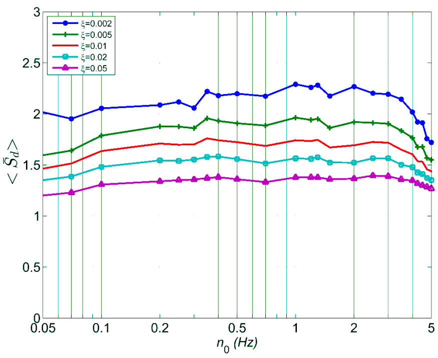
THUNDERSTORM RESPONSE SPECTRUM

Port of La Spezia, Genoa and Livorno



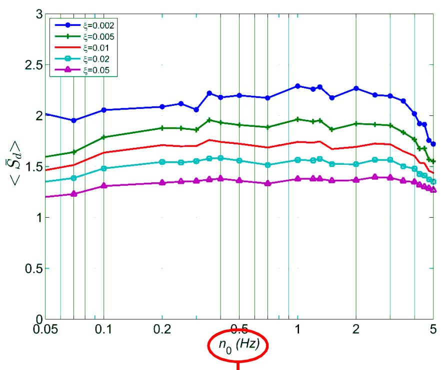
THUNDERSTORM RESPONSE SPECTRUM

Port of La Spezia, Genoa and Livorno

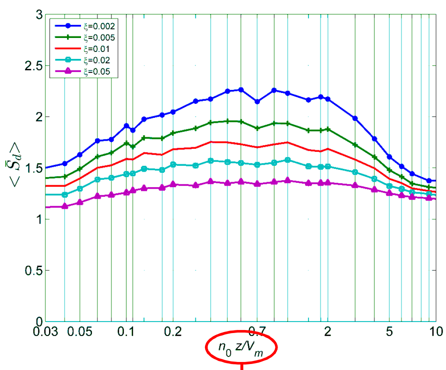


THUNDERSTORM RESPONSE SPECTRUM

Port of La Spezia, Genoa and Livorno



fundamental frequency



reduced fundamental frequency

RESPONSE SPECTRUM TECHNIQUE

1) **Single-Degree-Of-Freedom (SDOF) System**
   identically coherent wind field

2) **Multi-Degree-Of-Freedom (MDOF) System**
   multi-correlated wind field

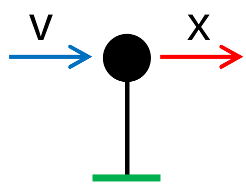
Solari et al., Eng. Struct., 2014a,b under submission.
Solari et al., Proc., 14th ICWE, Porto Alegre, Brasil, 2015, submitted.

Single-Degree-Of-Freedom system

$$\boxed{\ddot{d}(t)+2\xi\omega_0\dot{d}(t)+\omega_0^2 d(t)=\omega_0^2 u^2(t)}$$

$$\boxed{S_d = d_{max}(n_0,\xi)}$$

$$\boxed{x_{max} = \hat{x}_\tau \cdot S_d} \quad \boxed{f_{eq} = \hat{f}_\tau \cdot S_d}$$

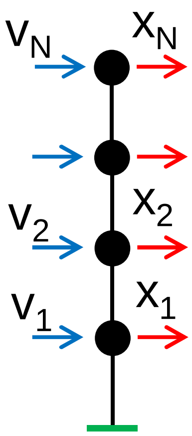


Multi-Degree-Of-Freedom system

$$\boxed{\ddot{d}_{eq}(t)+2\xi_1\omega_1\dot{d}_{eq}(t)+\omega_1^2 d_{eq}(t)=\omega_1^2 u_{eq}^2(\delta,t)}$$

$$\boxed{S_{d,eq} = d_{eq,max}(n_1,\xi_1,\delta)}$$

$$\boxed{x_{max}(z)=\psi_1(z)\cdot S_{d,eq}\cdot g_1} \quad \boxed{f_{eq}(z)=\hat{f}_\tau(z)\cdot S_{d,eq}}$$



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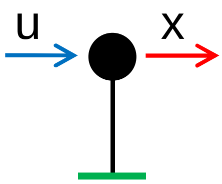

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$$S_{d,eq}=d_{eq,max}(n_1,\xi_1,\delta)$$

Limit solutions

1) **Point-like structure ($A \rightarrow 0$)**

2) **Infinitely large structure ($A \rightarrow \infty$)**

Multi-Degree-Of-Freedom system

$$\boxed{\ddot{d}_{eq}(t)+2\xi_1\omega_1\dot{d}_{eq}(t)+\omega_1^2 d_{eq}(t)=\omega_1^2 u_{eq}^2(\delta,t)}$$

$$\boxed{S_{d,eq}=d_{eq,max}(n_1,\xi_1,\delta)}$$

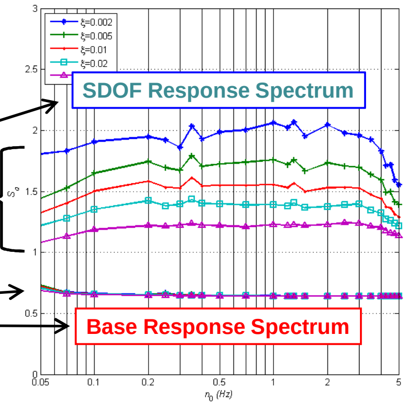
Limit solutions

1) Point-like structure ($A \rightarrow 0$)

$$\boxed{S_{d,eq}(n_1,\xi,\delta)=S_d(n_1,\xi)}$$

2) Infinitely large structure ($A \rightarrow \infty$)

$$\boxed{S_{d,eq}(n_1,\xi,\delta)=\bar{u}_{max}^2}$$



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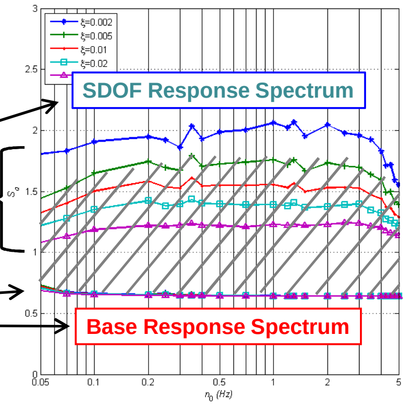

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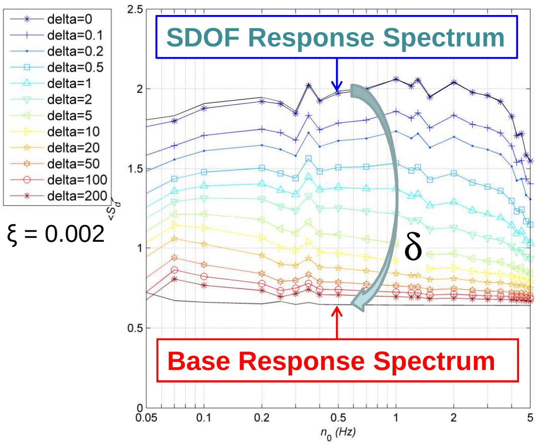

Multi-Degree-Of-Freedom system

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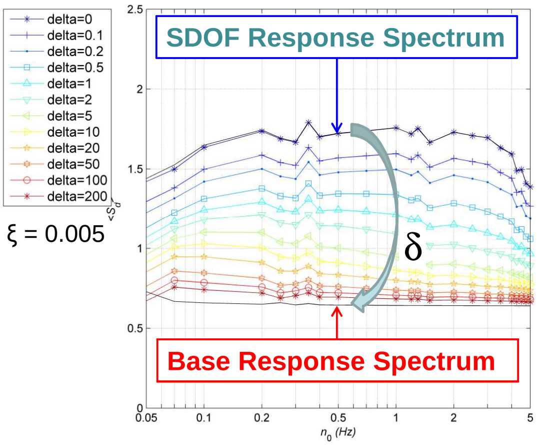

Multi-Degree-Of-Freedom system

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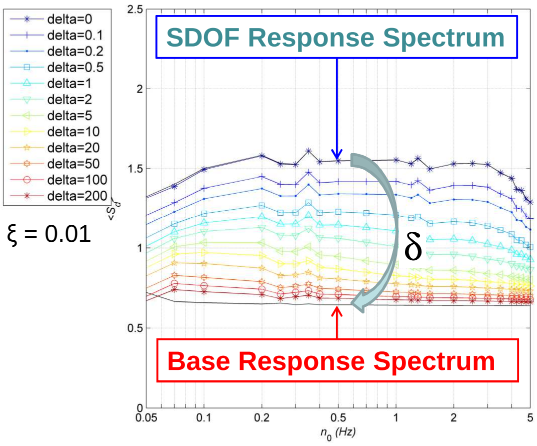

Multi-Degree-Of-Freedom system

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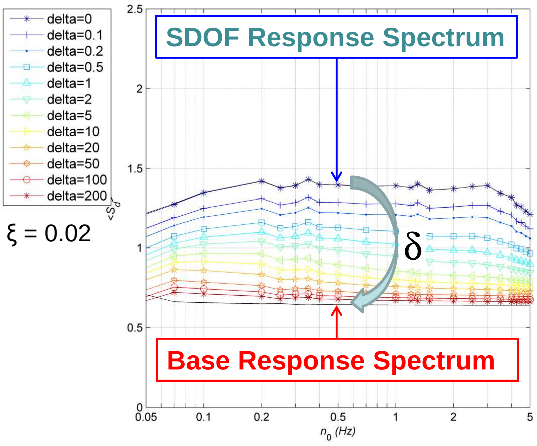
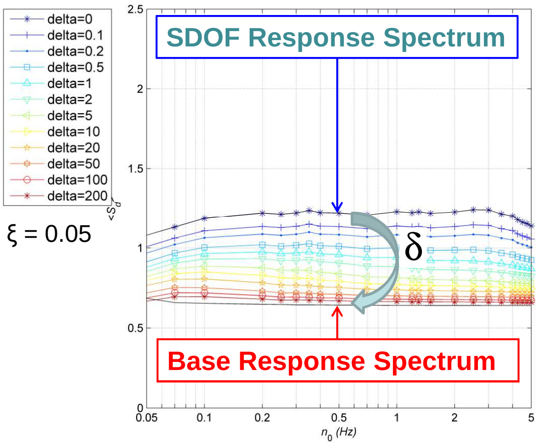


Multi-Degree-Of-Freedom system

$$\ddot{d}_{eq}(t) + 2\xi_1\omega_1\dot{d}_{eq}(t) + \omega_1^2 d_{eq}(t) = \omega_1^2 u_{eq}^2(\delta, t)$$

$$S_{d,eq} = d_{eq,max}(n_0, \xi, \delta)$$



Thunderstorm response spectrum technique

1) Determine the peak thunderstorm velocity $\hat{v}(h)$
2) Determine the thunderstorm velocity profile $\alpha(z)$
3) Determine the peak thunderstorm force

$$\hat{f}(z) = \frac{1}{2}\rho\hat{v}^2(h)\alpha^2(z)b(z)c_d(z)$$

Thunderstorm response spectrum technique

1) Determine the peak thunderstorm velocity $\hat{v}(h)$
2) Determine the thunderstorm velocity profile $\alpha(z)$
3) Determine the peak thunderstorm force

$$\hat{f}(z)=\frac{1}{2}\rho\hat{v}^2(h)\alpha^2(z)b(z)c_d(z)$$

4) Determine the structural damping ξ
5) Determine the natural frequency n_0
6) Determine the size parameter δ

$$\delta=\frac{kCh}{\bar{u}(h)\alpha(z_{eq})}$$

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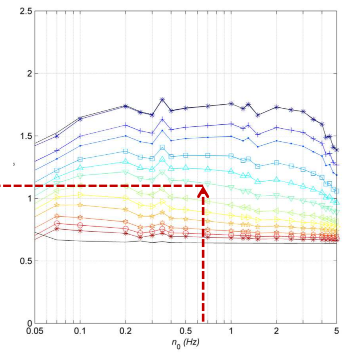

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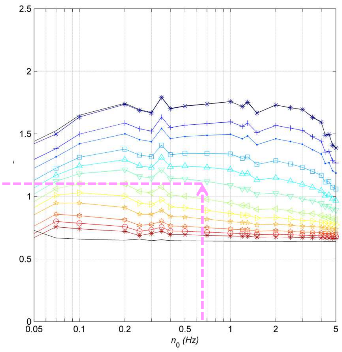
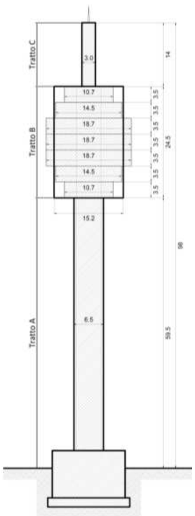
8) Determine the equivalent static force

$$f_{eq}(z) = \hat{f}(z) \cdot S_{d,eq}$$



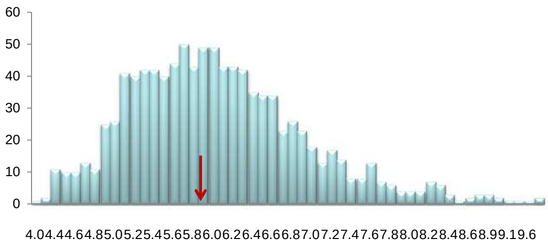
MONTE CARLO SIMULATION

Mediaset Tower, Cologno Monzese



Top displacement

Monte Carlo simulation x(h) = 5.84 cm



Response spectrum technique x(h) = 5.88 cm

In all cases, error less than 1%

Reliability-based calibration of partial factors for the future evolution of EN 1990 for wind actions

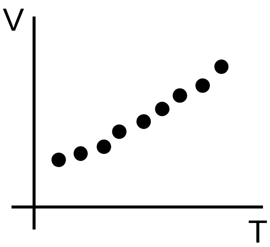
CEN/TC250/WG7 – Delft, The Netherlands, February 17, 2015

Thunderstorm monitoring, statistics and loading of structures

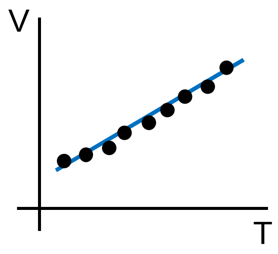
Wind loading on structures

WinDyn

DESIGN WIND VELOCITY



DESIGN WIND VELOCITY



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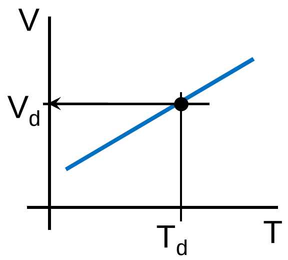

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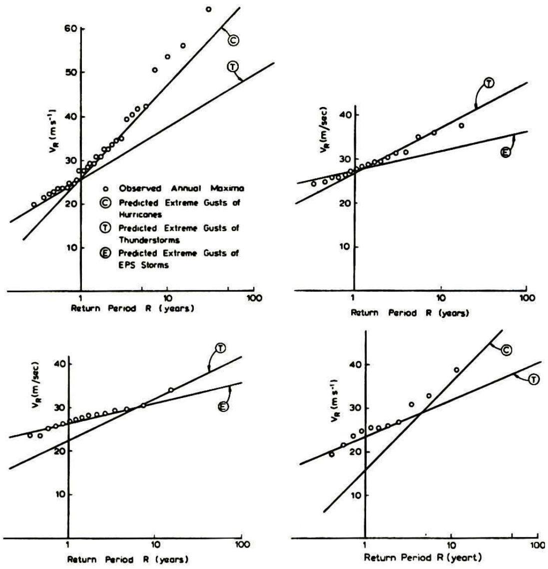
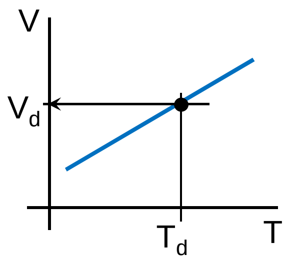




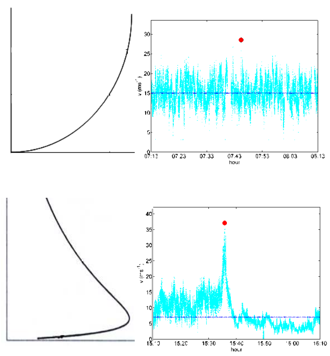
Gomes & Vickery (1977/1978)

DESIGN WIND VELOCITY

Wind Data

Extra-tropical Depressions

Thunder-storms



Gomes & Vickery (1977/1978)

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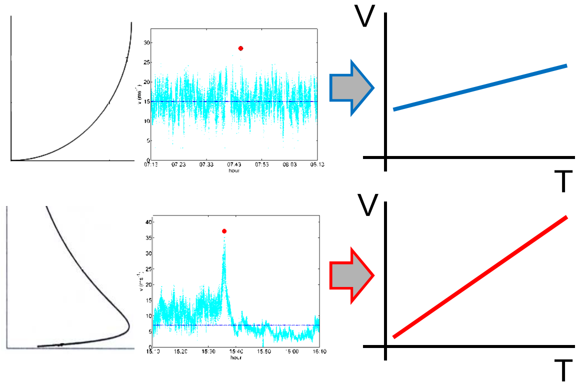

Gomes & Vickery (1977/1978)

DESIGN WIND VELOCITY

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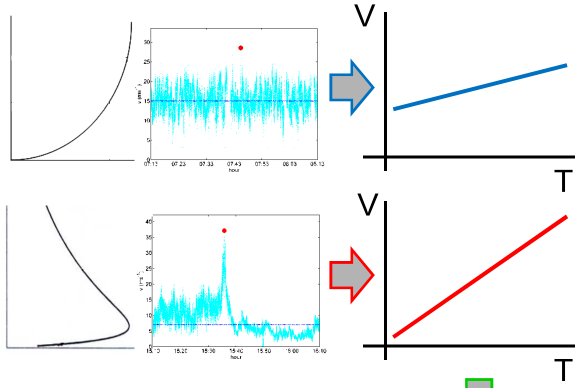
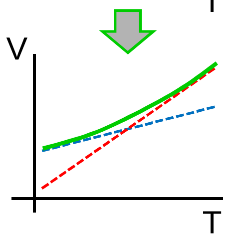
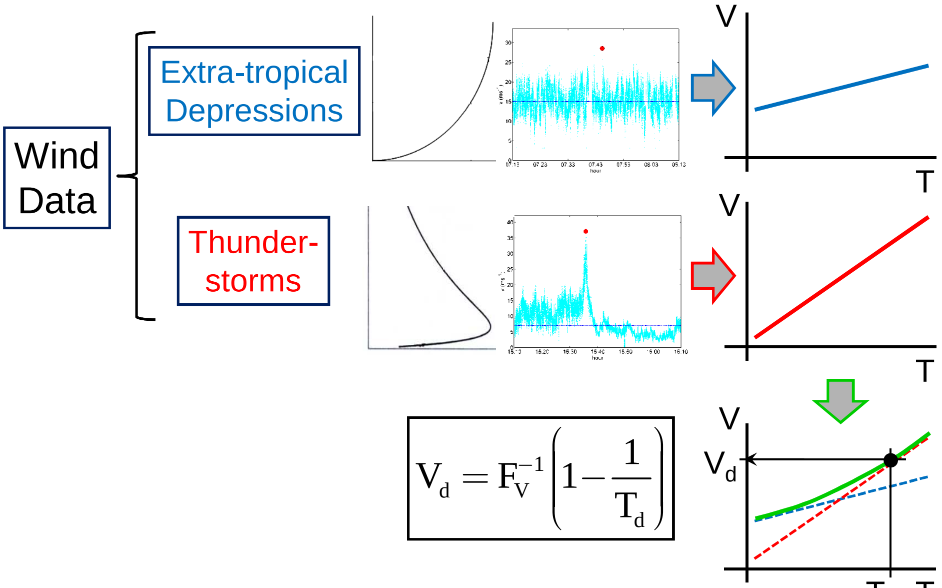


$$F_V(v) = F_{VD}(v) \cdot F_{VT}(v)$$



Gomes & Vickery (1977/1978)

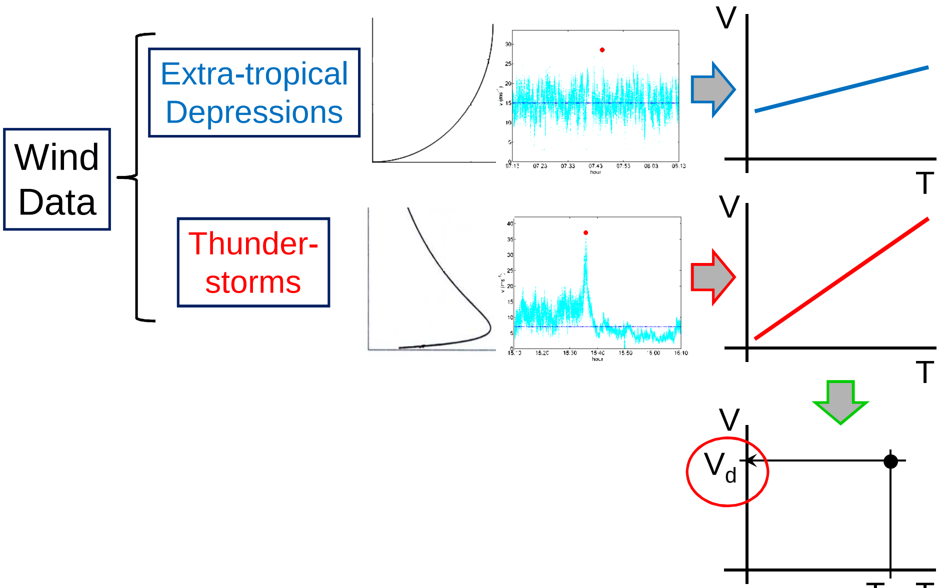
DESIGN WIND VELOCITY



$$V_d = F_V^{-1}\left(1 - \frac{1}{T_d}\right)$$

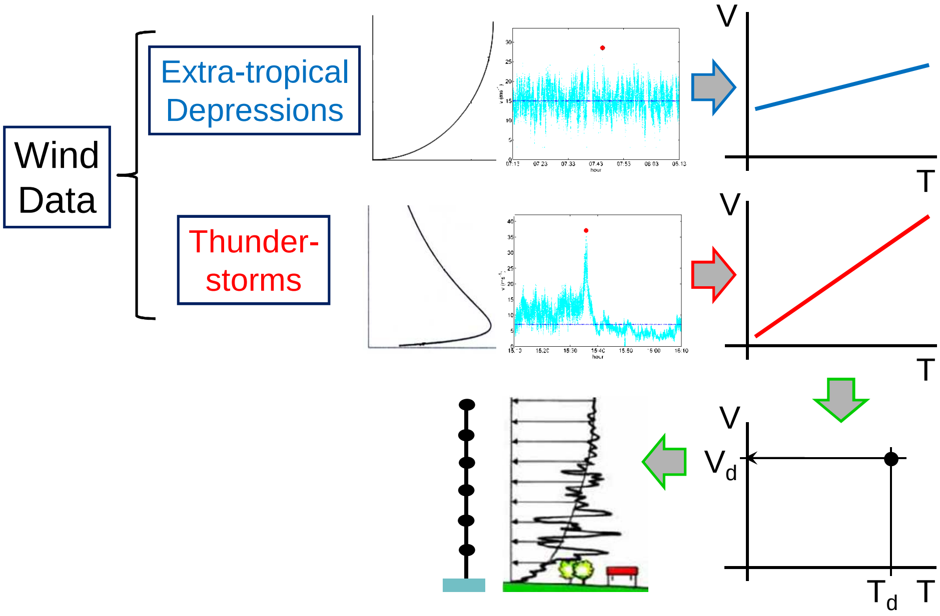
Gomes & Vickery (1977/1978)

DESIGN WIND VELOCITY

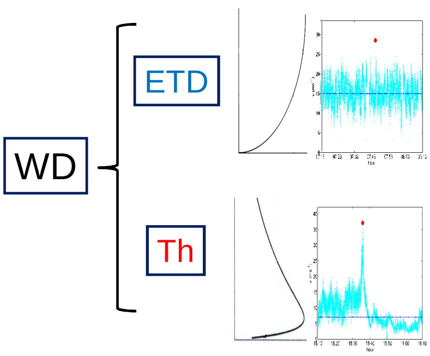


Gomes & Vickery (1977/1978)

DESIGN WIND VELOCITY

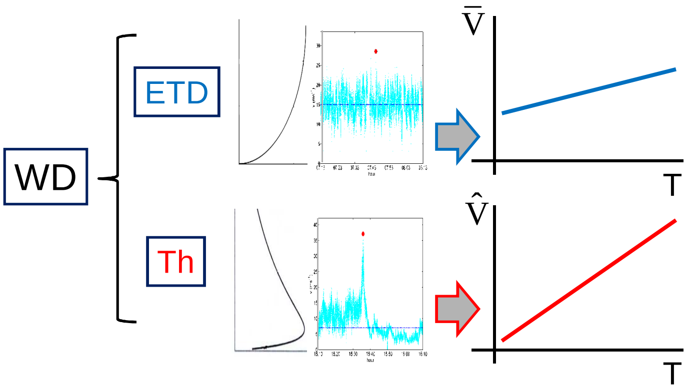


INDEPENDENT LOADINGS TECHNIQUE



Solari (2013), Solari *et al*. (2013, 2014)

INDEPENDENT LOADINGS TECHNIQUE



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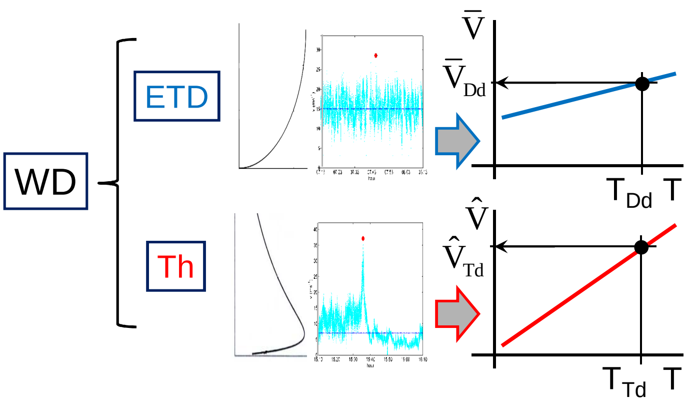

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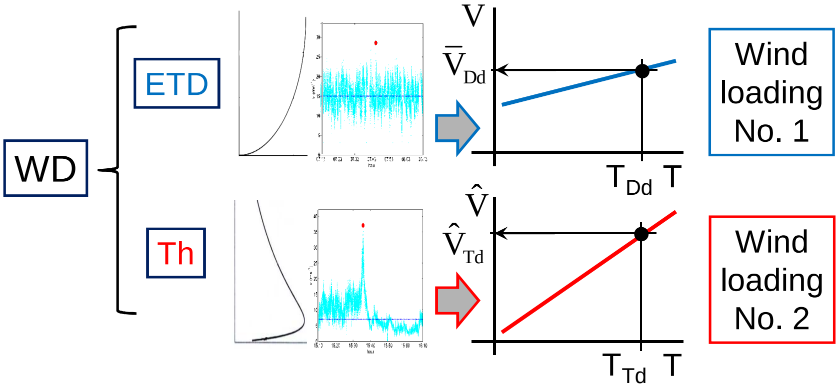

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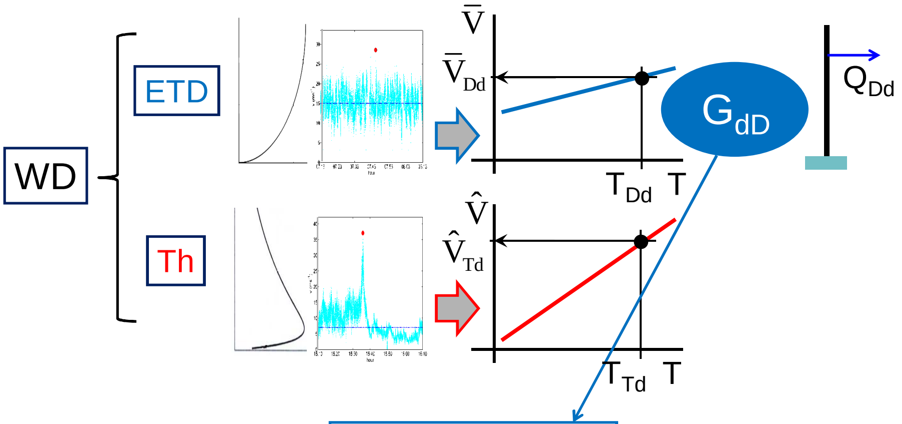
INDEPENDENT LOADINGS TECHNIQUE

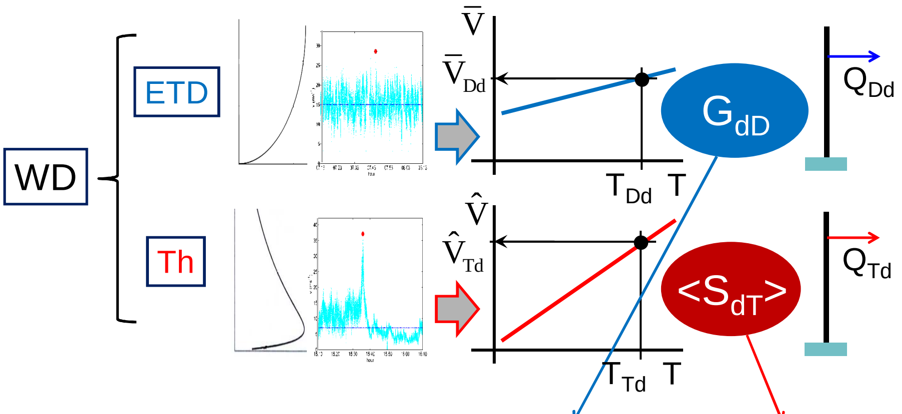


Equivalent static pressure

$$\boxed{Q_{Dd} = \frac{1}{2}\rho \bar{V}_{Dd}^2 \cdot G_{dD}}$$

Solari (2013), Solari *et al*. (2013, 2014)

INDEPENDENT LOADINGS TECHNIQUE



Equivalent static pressure

$$Q_{Dd} = \frac{1}{2}\rho \bar{V}_{Dd}^2 \cdot G_{dD}$$

$$Q_{Td} = \frac{1}{2}\rho \hat{V}_{Td}^2 \cdot \langle S_{dT} \rangle$$

Solari (2013), Solari *et al*. (2013, 2014)

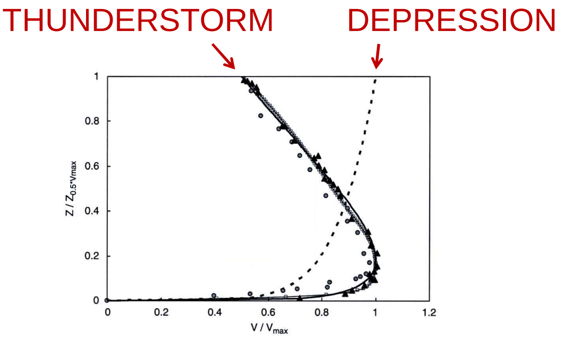
INDEPENDENT LOADINGS TECHNIQUE

There are several reasons that robustly support the application of the independent (wind) loadings technique:

INDEPENDENT LOADINGS TECHNIQUE

There are several reasons that robustly support the application of the independent (wind) loadings technique:

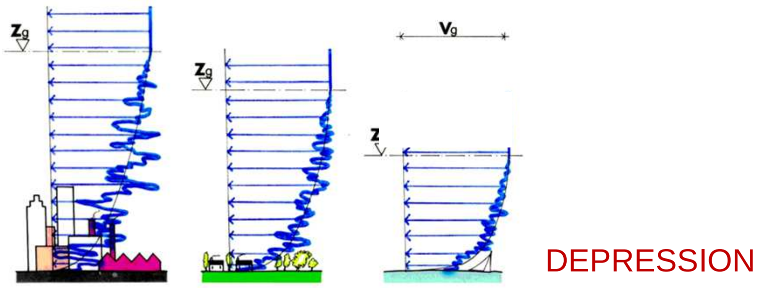
1) Different wind events are endowed with different velocity profiles



INDEPENDENT LOADINGS TECHNIQUE

There are several reasons that robustly support the application of the independent (wind) loadings technique:

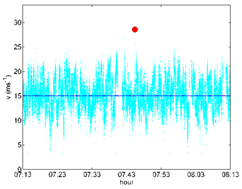
2) They are characterized by different parameterization rules for roughness length, topography and thermal stratification that lead to different transferring tools from one site to another



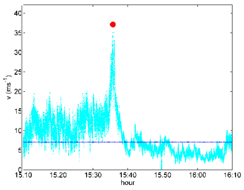
INDEPENDENT LOADINGS TECHNIQUE

There are several reasons that robustly support the application of the independent (wind) loadings technique:

3) The different stationary/non-stationary and Gaussian/non-Gaussian character of wind velocity causes different structural responses



DEPRESSION

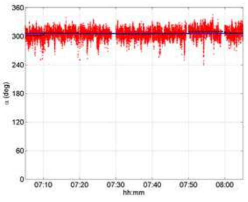


THUNDERSTORM

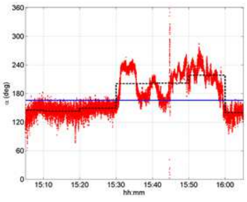
INDEPENDENT LOADINGS TECHNIQUE

There are several reasons that robustly support the application of the independent (wind) loadings technique:

4) The application of directional coefficients calibrated for depressions to thunderstorms distorts reality and forces the application of related concepts and rules outside their correct domain



DEPRESSION



THUNDERSTORM

INDEPENDENT LOADINGS TECHNIQUE

There are several reasons that robustly support the application of the independent (wind) loadings technique:

5) Different wind events have different distributions, extensions and durations that imply different partial safety factors and different combination coefficients

$$\boxed{C_F = \gamma_{G1} \cdot G_1 + \gamma_{G2} \cdot G_2 + \gamma_P \cdot P + \gamma_{Q1} \cdot Q_{k1} + \gamma_{Q2} \cdot \psi_{02} \cdot Q_{k2} +}$$

Solari (2013), Solari *et al*. (2013, 2014)

INDEPENDENT LOADINGS TECHNIQUE

Based upon the above properties the Independent Loading Technique involves several advantages:

Solari (2013), Solari *et al*. (2013, 2014)

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1. It provides an appropriate representation and evaluation of each different wind phenomenon.

Solari (2013), Solari *et al*. (2013, 2014)

INDEPENDENT LOADINGS TECHNIQUE

Based upon the above properties the Independent Loading Technique involves several advantages:

1. It provides an appropriate representation and evaluation of each different wind phenomenon.
2. It does not modify the spirit of engineering analyses and regulatory schemes currently in use. It simply adds some new rules in the classical spirit.

Solari (2013), Solari *et al*. (2013, 2014)

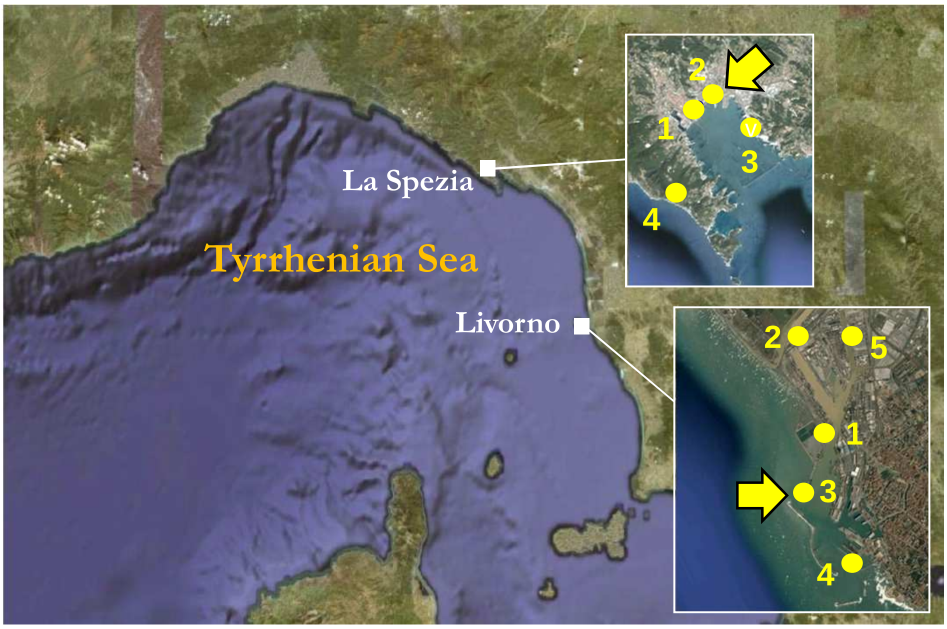
INDEPENDENT LOADINGS TECHNIQUE

Based upon the above properties the Independent Loading Technique involves several advantages:

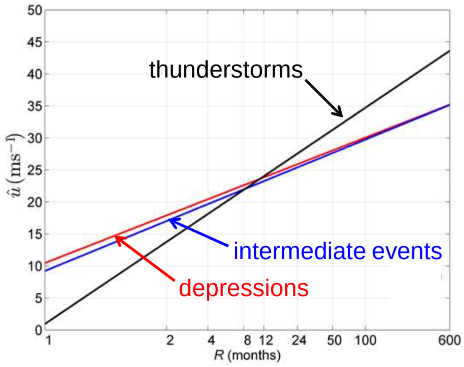
1. It provides an appropriate representation and evaluation of each different wind phenomenon.
2. It does not modify the spirit of engineering analyses and regulatory schemes currently in use. It simply adds some new rules in the classical spirit.
3. It can be easily generalized to any number of wind loading mechanisms (tornadoes, tropical ciclones, downslope winds, intermediate events, …), simply adding each of these as a new independent wind loading condition.

Solari (2013), Solari *et al*. (2013, 2014)

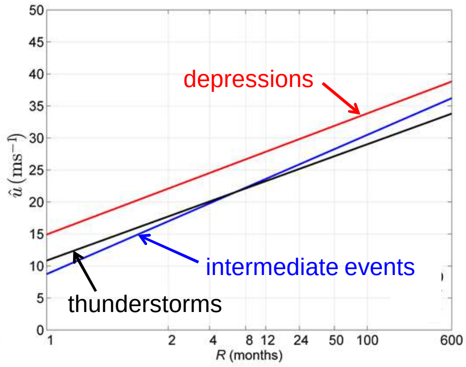
“Wind & Ports” Project monitoring network



Distribution of the maximum peak wind velocity

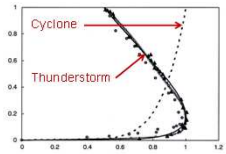


Anemometer 2
Port of La Spezia

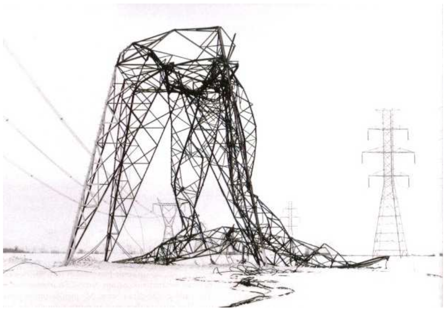


Anemometer 3
Port of Livorno

LOW/MID-RISE STRUCTURES



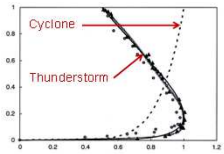
LOW/MID-RISE STRUCTURES




LOW/MID-RISE STRUCTURES



HIGH-RISE STRUCTURES



http://www.windyn.com

Workshop

Reliability based calibration of partial factors for future evolution of EN 1990 for wind actions

Delft – 17-18 february 2015

Influence of extreme load models for wind pressure on structural reliability

Pietro Croce

Univ. of Pisa

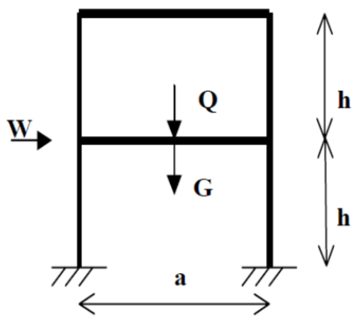


Figure 3.1. Two storey steel frame

$$Z = R - 0.16\, m_E\, h\, (G + Q + W)$$

JCSS PROBABILISTIC MODEL CODE

EXAMPLE APPLICATIONS

Ton Vrouwenvelder

Milan Holicky

Jana Markova

$$R = m_R Z_p f_y$$

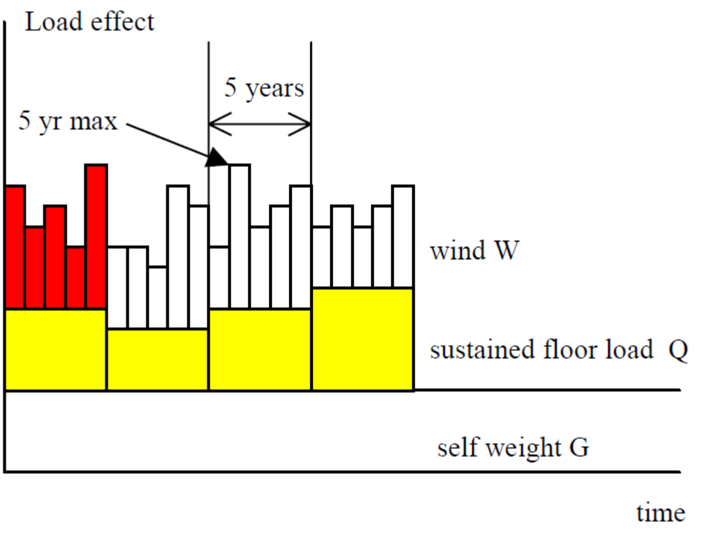
$$G = a\, b\, t\, \rho_c\, g$$

$$Q = a\, b\, (q_{long} + q_{short})$$

$$W = 2\, h\, b\, c_a\, c_g\, c_r\, (0.5\, m_q\, \rho_a\, U^2)$$

Table 3.1 Probabilistic models for the steel frame example (according to the JCSS Probabilistic Model Code 2001)

X	Designation	Distribution	Mean	V	λ
a	in plane column distance	Deterministic	6 m	-	
b	frame to frame distance	Deterministic	5 m	-	
h	storey height	Deterministic	3 m	-	
t	thickness concrete floor slab	Normal	0.20 m	0.03	
Z_p	plastic section modulus	Normal	$0.0007m^3$	0.02	
f_y	steel yield stress	Lognormal	300 MPa	0.07	
g	acceleration of gravity	Deterministic	$10\ m/s^2$	-	
ρ_c	mass density concrete	Normal	$2.4\ ton/m^3$	0.04	
q_{long}	long term live load (sustained)	Gamma	$0.50\ kN/m^2$	1.15	0.2/year
q_{short}	short term live load (1 day)	Exponential	$0.20\ kN/m^2$	1.60	1.0/year
ρ_a	mass density air	Deterministic	$0.125kg/m^3$	-	
c_a	aerodynamic shape factor	Normal	1.10	0.12	
c_g	gust factor	Normal	3.05	0.12	
c_r	roughness factor	Normal	0.58	0.15	
u	ref wind speed (8 hours)	Weibull	5 m/s	0.60	3.0/day
U	ref wind speed (one year)	Gumbel	30 m/s	0.10	1.0/year
m_q	model factor wind pressure	Normal	0.80	0.20	
m_R	model factor resistance	Normal	1.00	0.05	
m_E	model factor load effect	Normal	1.00	0.10	



Cases considered for extreme wind velocity

Gumbel distribution

3-parameters Weibull distribution

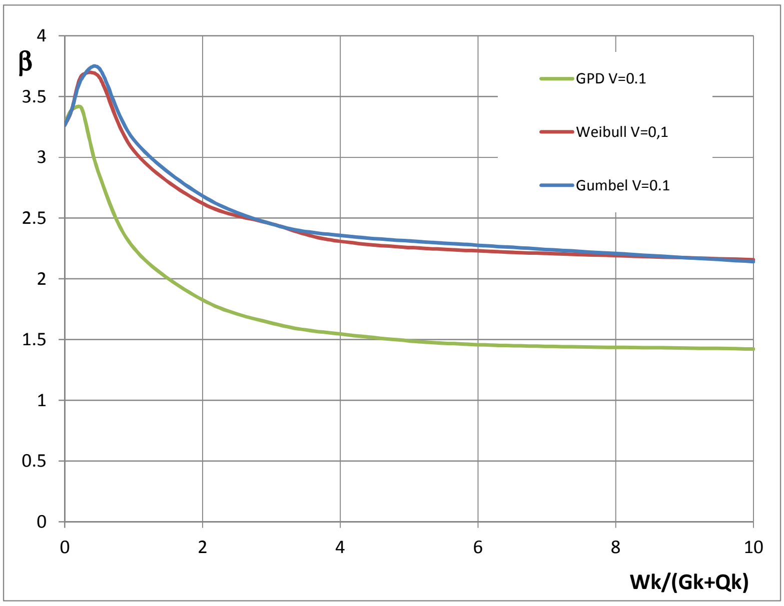
GPD

V=0.1

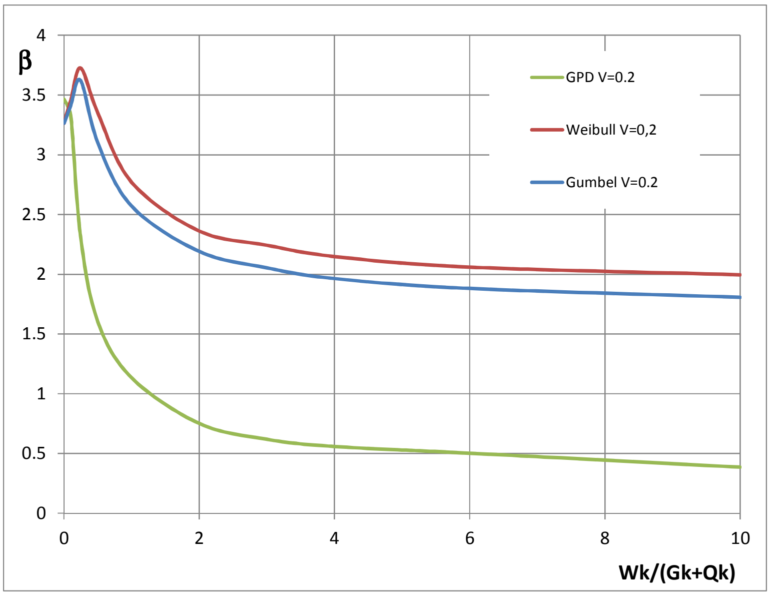
V=0.2

$W_k/(G_k+Q_k)$
0
0.1
0.245
0.5
1
2
3
4
6
10

Steel S275 – V=0.07



β-$W_k/(G_k+Q_k)$ diagrams for various extreme maxima distributions for wind (V=0.1)



β-$W_k/(G_k+Q_k)$ diagrams for various extreme maxima distributions for wind (V=0.2)

Conclusions

Reliability decreases when the wind action is very high

Reliability depends on the distribution assumed for extreme maxima

Wind pressure model is still an open question (each relevant coefficient needs a deep discussion)

Thank you for your attention

JCSS
Joint Committee
on Structural
Safety

Wind actions on structures

Uncertainties and bias of Eurocode estimates

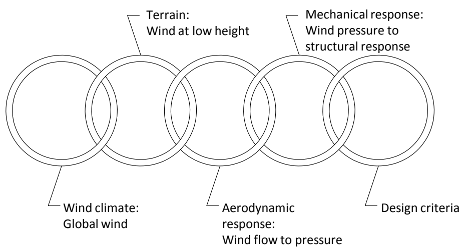
Svend Ole Hansen ApS

JCSS
Joint Committee
on Structural
Safety

Eurocode on wind actions

- The first Eurocode on wind actions, ENV 1991-2-4:1995
- Revised Eurocode version, EN 1991-1-4:2005

Wind load chain



Eurocode on snow load

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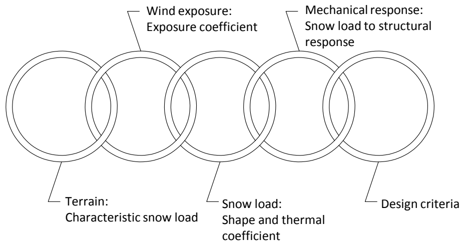
- The first Eurocode on snow loads, ENV 1991-2-3:1995
- Revised Eurocode version, EN 1991-1-3-2007

Snow load chain



Wind climate

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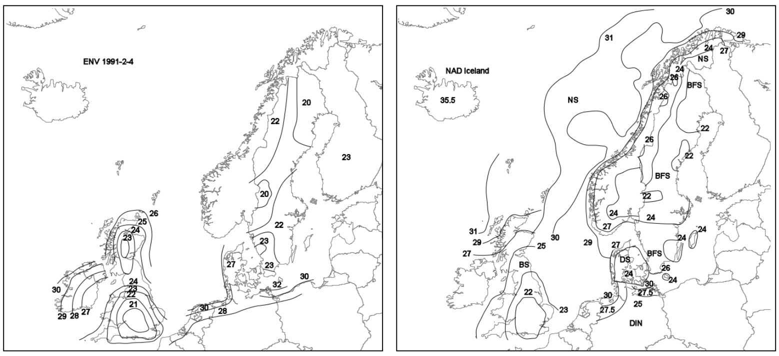
Basic wind velocities in North Europe



ENV 1991-2-4:1995

National Annexes to EN 1991-1-4:2005

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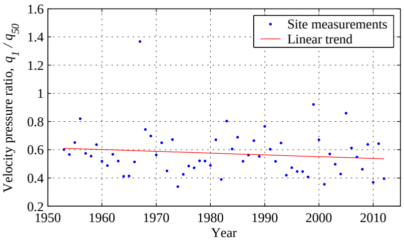
Joint Committee on Structural Safety

Wind climate

Climate changes?



Annual extremes in Denmark, based on site measurements.

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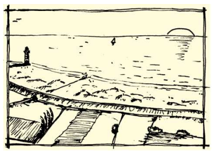
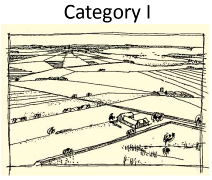
Joint Committee on Structural Safety

Terrain categories

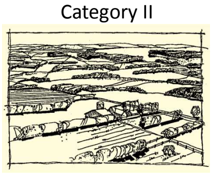
Category 0



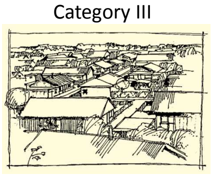
Category I



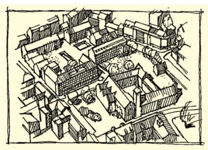
Category II



Category III



Category IV



Wind-induced pressures on a one layer façade

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Which pressure coefficient c_{pe} provides a characteristic wind pressure calculated by $w_e = c_{pe}\, q_p$, in which q_p is the characteristic peak velocity pressure?

Wind-induced pressures on a one layer façade

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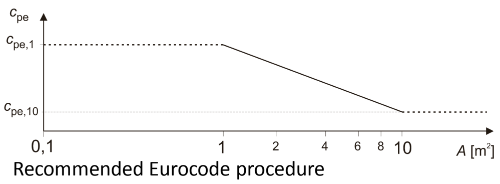
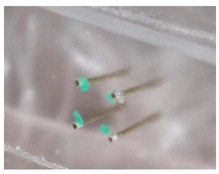


Recommended Eurocode procedure



Pressure tap cluster on model

- For 1 m² loaded areas the measurements show larger suctions than the Eurocode value of -1.4 for facades. This may partly originate from the fact that each pressure tap has an area of less than 1 m².
- For 10 m² loaded areas the measurements show lower suctions than the Eurocode value of -1.2 for facades. Thus, the spatial averaging applied in the wind tunnel gives larger reductions than the Eurocode.

Experience from wind tunnel testing

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The experience gained from a large number of wind tunnel tests carried out with models of a variety of different building geometries is as follows:

1. The Eurocode 1 m² pressure coefficients often underestimate the wind action measured in the wind tunnel. An **underestimation** of more than 20% is often observed
2. The Eurocode 10 m² pressure coefficients often overestimate the wind action measured in the wind tunnel. An **overestimation** of more than 20% is often observed.
3. The Eurocode global wind action often overestimates the wind action measured in the wind tunnel. Often the **overestimation** is of an order of at least 40%.

Experience from wind tunnel testing

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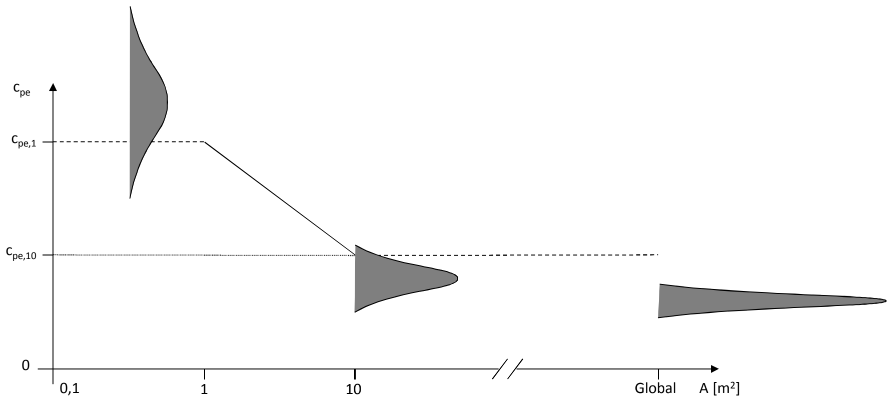

Wind-induced pressures on a one layer façade

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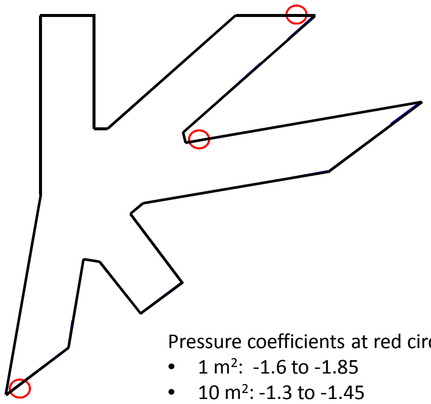
UN-city in Copenhagen, Denmark



Pressure coefficients at red circles

- 1 m^2: -1.6 to -1.85
- 10 m^2: -1.3 to -1.45

1:200 wind tunnel scale model of the UN-city

Wind-induced pressures on a one layer façade

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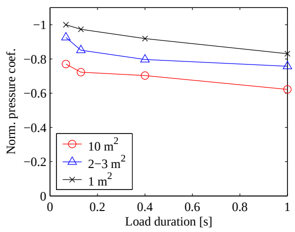
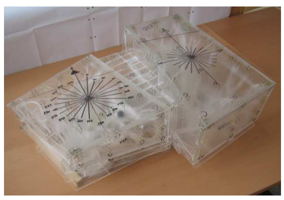
The Concert and Conference Centre “Harpa” in Reykjavik, Iceland





1:200 wind tunnel scale model

Wind-induced pressures on a one layer façade

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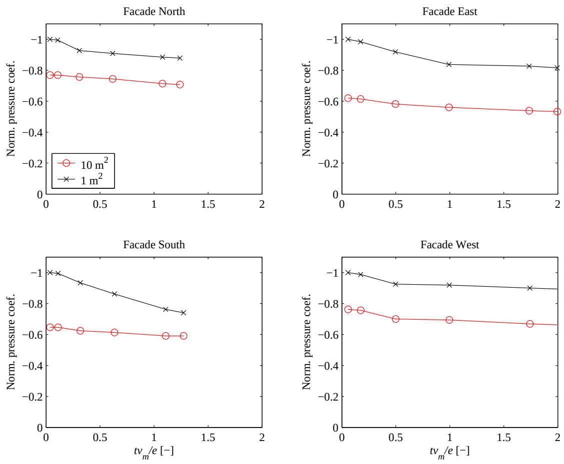
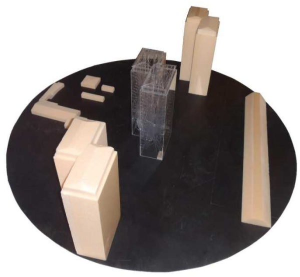
Søndermarken in Copenhagen, Denmark





1:200 wind tunnel scale model of block building

Wind-induced pressures on a two skin façade

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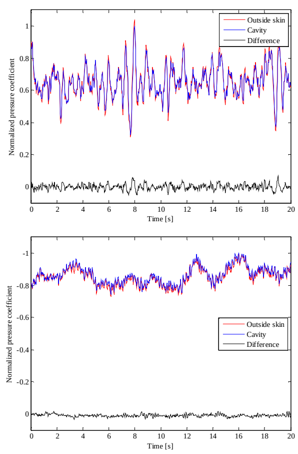
Søndermarken in Copenhagen, Denmark



1:25 wind tunnel scale model of block building in the large wind tunnel of SOH Wind Engineering in Vermont, USA

Wind-induced global loads

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Characteristic wind load specified in EN 1991-1-4:2005

$$F_w = q_p \, c_s c_d \, c_f \, A_{ref}$$

q_p : Characteristic peak velocity pressure at reference height

$c_s c_d$: Structural factor which comprises of a size effect and a dynamic amplification effect

c_f : Force coefficient

A_{ref} : Reference area

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Wind-induced global loads

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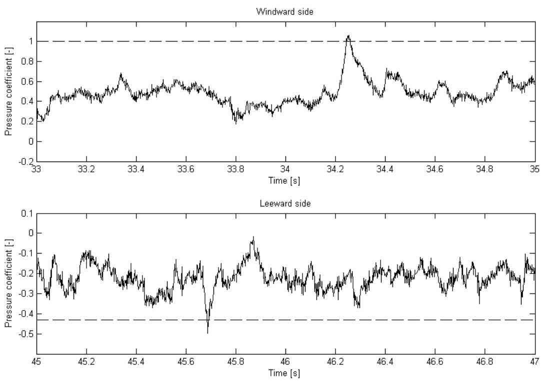
SiteCover



1:75 wind tunnel scale model of SiteCover

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Wind-induced global loads

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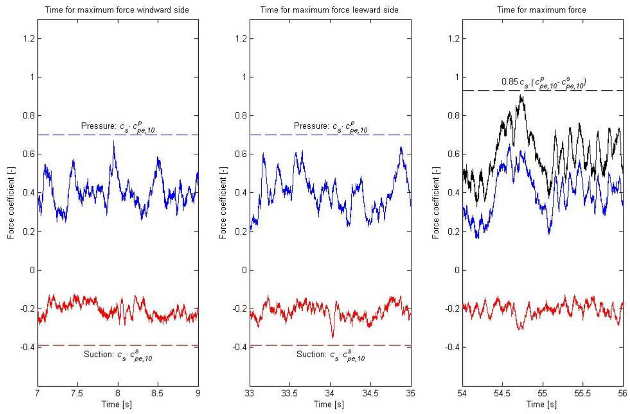
SiteCover



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CAARC standard tall building model

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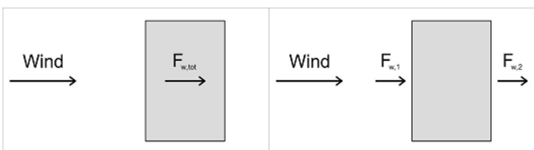
Federico Pastorino, M.Sc.
Giovanni Solari, Prof.
University of Genova



Decomposition of the global along-wind equivalent static load.

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CAARC standard tall building model

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Giovanni Solari, Prof.
University of Genova

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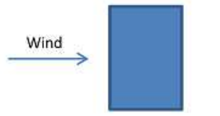
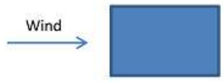
Change of roughness length

Change of shape

ρ (NN306,SS306)			
A000	A180	B000	B180
-0.463	-0.345	-0.191	-0.283
-0.404		-0.237	



ρ (NN306,SS306)			
A090	A270	B090	B270
-0.468	-0.388	-0.267	-0.249
-0.428		-0.258	



Values of the correlation between two representative pressure taps, respectively on the windward and leeward façades.

CAARC standard tall building model

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Giovanni Solari, Prof.
University of Genova

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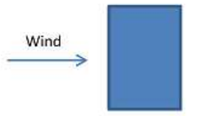
Change of roughness length

Change of shape

$\rho(TotF_N, TotF_S)$			
A000	A180	B000	B180
-0.679	-0.559	-0.355	-0.458
-0.619		-0.406	



$\rho(TotF_N, TotF_S)$			
A090	A270	B090	B270
-0.637	-0.568	-0.468	-0.474
-0.602		-0.471	

Values of the correlation between the pressures integrated separately on the windward and leeward façades.

Mechanical response

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1. Influence lines or mode shapes with changing signs.
2. Vortex-induced vibrations.
3. Galloping-induced vibrations.
4. Aeroelastic effects for cross section 1:2, where vortex-induced and galloping-induced vibrations interact.

Vortex-induced vibrations

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Scruton number

$$Sc = \frac{2\delta_s m_e}{\rho b^2}$$

General non-dimensional mass-damping parameter

$$Sc_G = \frac{2\delta_s m_e}{\rho b d}$$

δ_s : Structural damping

m_e : Mass of structure per unit length

ρ : Air density

b : Cross-wind width

d : Along-wind depth

Vortex-induced vibrations

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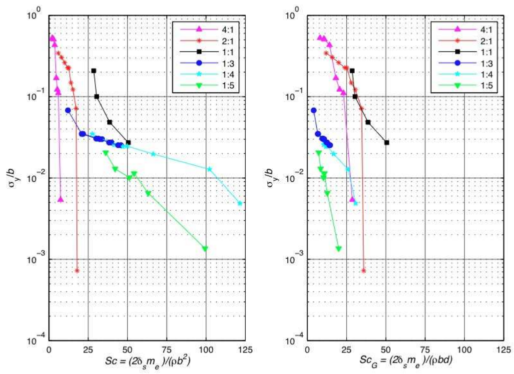
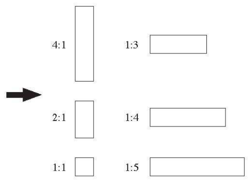


Measured vortex –induced vibrations



Tested cross sections

Galloping and vortex-induced vibrations

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$$v_{CG} = 2Sc_G n_e b / a_{GG}$$

$$\delta_{aG} = -\frac{\rho d v_m}{4 m_e n_e} a_{GG}$$

$$a_{GG} = -\left(\frac{dC_L}{d\theta} + C_D \right)$$

$$\delta_a = \delta_{KaG} + \delta_{aG}$$

Galloping and vortex-induced vibrations

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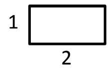
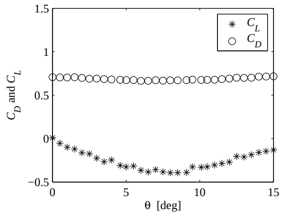
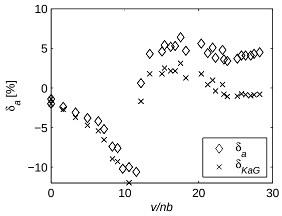
Aeroelastic effects for 1:2 cross section





The lift and drag coefficient as a function of angle of attack



Negative aerodynamic damping (positive y-values) given by a logarithmic decrement

Galloping and vortex-induced vibrations

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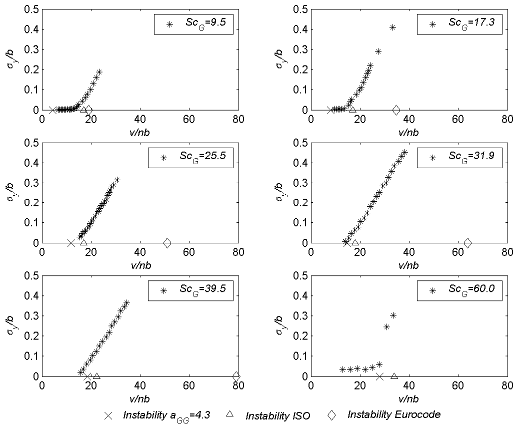
Aeroelastic effects for 1:2 cross section



Wind-induced vibrations of a 1:2 cross section at different mass-damping parameters

Design Criteria

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- Future codes are expected to focus much more on the structural resistance relevant for fluctuating wind effects.
- Present Eurocode revision: focus area is wind loads relevant for structures, where their resistance increases for shorter load durations, e.g. glass panels.

Experimental arrangement for testing glass resistance as function of load duration

Conclusion – Wind actions

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- Further harmonisation.
- Building codes should be probability based, so data used in the codes should also be probability based.
- The analysis techniques should be consistent with the choices made for the level of safety in the building codes.
- The relation between averaging time and spatial averaging, and the choice of extreme value analysis should be consistent with the probabilistic approach applied.
- Flow conditions and measurements techniques should be known and be within the range of applicability of the codes.

Wind load distribution

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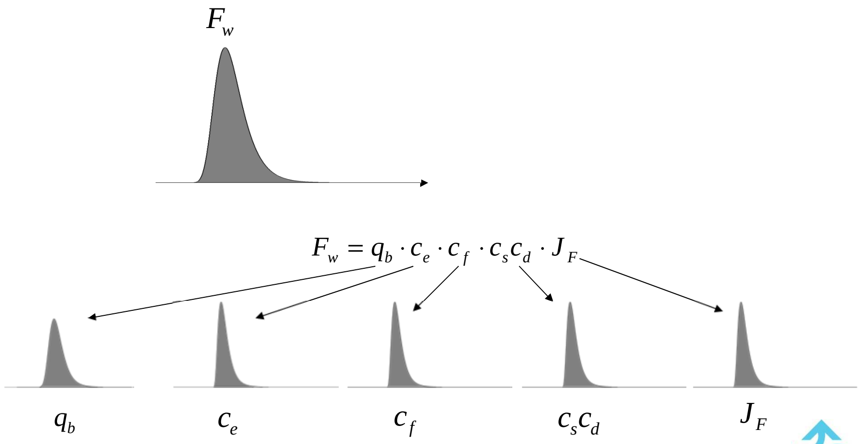

$$F_w = q_b \cdot c_e \cdot c_f \cdot c_s c_d \cdot J_F$$

Snow load distribution

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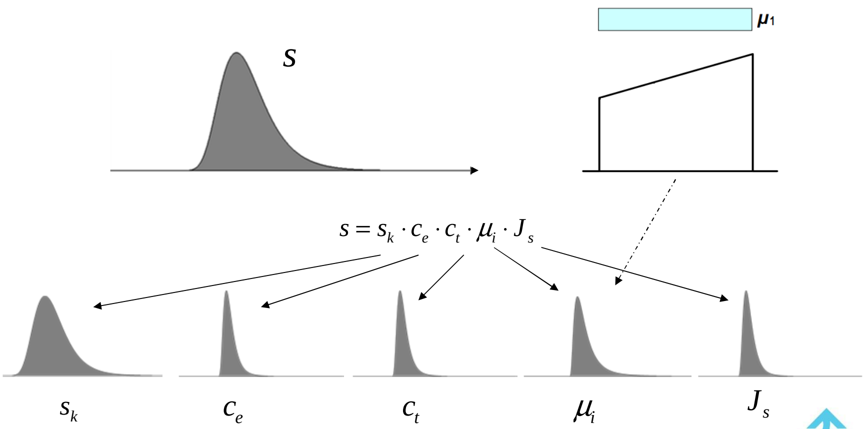

$$s = s_k \cdot c_e \cdot c_t \cdot \mu_i \cdot J_s$$

Snow load distribution

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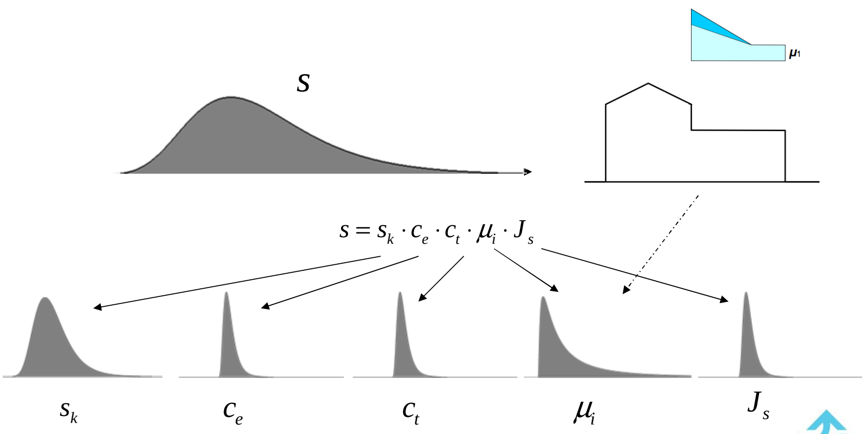

Uncertainty of shape coefficients

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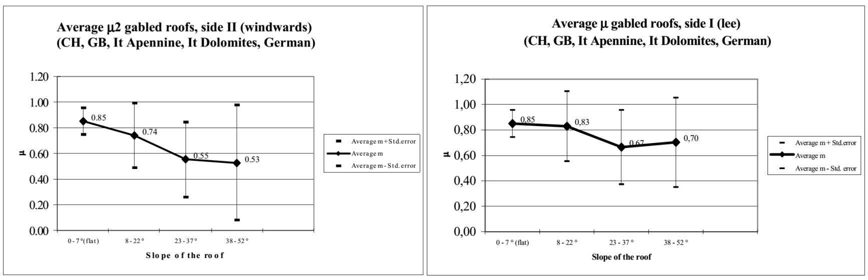

Mean and standard deviation of the roof shape coefficient for gabled roofs with different slopes for Swiss, Italian Apennine, Italian Dolomites, United Kingdom and German sites.

Commission of the European Communities
DGIII – D3
Scientific Support Activity in the Field of Structural Stability of Civil Engineering Works
Snow Loads
1997

Comparison of distributions

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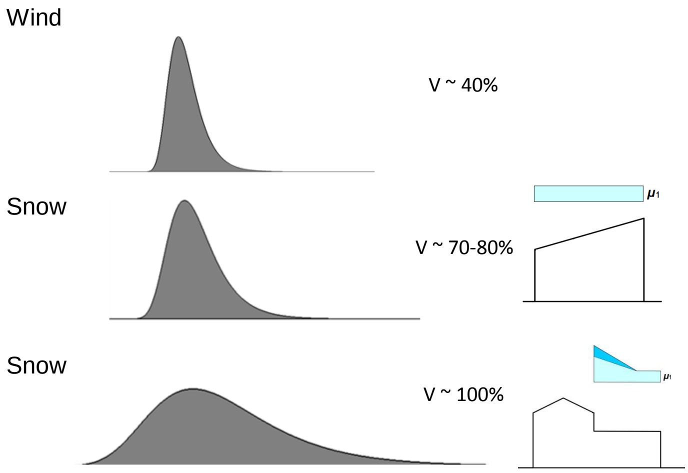

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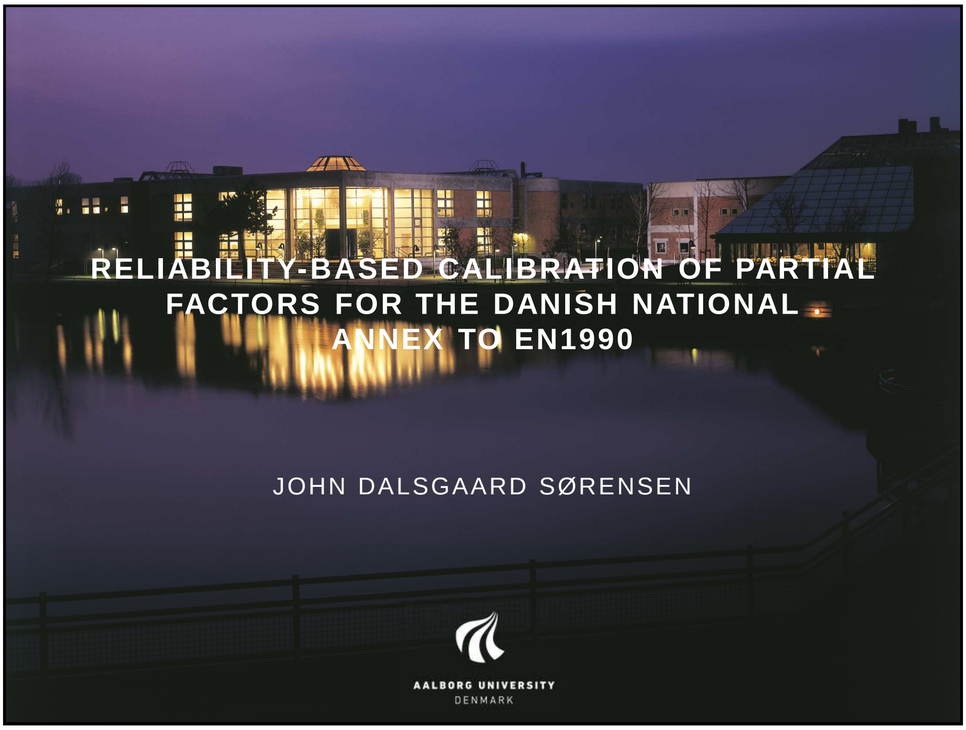
Thanks for your attention

Svend Ole Hansen ApS



Introduction

AALBORG UNIVERSITY DENMARK

The partial factors in the Danish National Annexes for buildings have been chosen using a reliability-based approach

Main objectives and choices for the calibration

- To have as far as possible a uniform reliability with respect to
    - Different types of materials (concrete, steel, timber, soil, ….)
    - Different types of loads (permanent loads, wind loads, snow loads, imposed loads, …)
    - Different load combinations (STR: design of structural components, EQU: static equilibrium and GEO: geotechnical design)
- …

Introduction

- …
- To have a partial safety factor equal to 1.0 on permanent load in the load combination for ULS for design of structural components where variables loads are dominating.
- To have consequence classes that correspond to the safety classes used in the old Danish code DS409 (2008).
- To have the same basic load combinations and partial safety factors for geotechnical design as for design of structural components.

Load combinations in DK NA EN1990

Load combinations:

- STR and GEO:

STR (6.10b): $E_d ' = ' \sum_j \gamma_{GAj} G_{k,j} "+" \gamma_Q Q_{k,1} "+" \sum_{j>1} \gamma_Q \psi_j Q_{k,j}$

STR (6.10a): $E_d ' = ' \sum_j \gamma_{GBj} G_{k,j}$

- EQU:

EQU (6.10): $E_d ' = ' \sum_{stab} \gamma_{GGC} G_{k,j} "+" \sum_{driv} \gamma_{GUC} G_{k,j} "+" \gamma_Q Q_{k,1} "+" \sum_{j>1} \gamma_Q \psi_j Q_{k,j}$

- K_{FI} factor on unfavourable loads:

Consequence class	Low – CC1	Medium – CC2	High – CC3
K_{FI}	0,90	1,00	1,10

Load combinations in DK NA EN1990

Table A1.2(A) DK NA Design values of actions for persistent and transient design situat (EQU and UPL) (Set A)

Limit state				EQU / UPL	UPL
Combination of actions				1	2
Reference formula				(6.10)	(6.10)
Permanent action	Weight, general (**)	Unfavourable	$\gamma_{Gj,sup}$	$1{,}1 \cdot K_{FI}$	$1{,}0 \cdot K_{FI}$
		Favourable	$\gamma_{Gj,inf}$	0,9	1,0
	Weight of soil and (ground) water, geotechnical structures (***)	Unfavourable	$\gamma_{Gj,sup}$	$1{,}1 \cdot K_{FI}$	$1{,}05 \cdot K_{FI}$
		Favourable	$\gamma_{Gj,inf}$	0,9	1,0
Variable action (*)	Leading	Unfavourable	$\gamma_{Q,1}$	$1{,}5 \cdot K_{FI}$	$1{,}5 \cdot K_{FI}$
	Other	Unfavourable	$\gamma_{Q,i}$	$1{,}5 \cdot \psi_0 \cdot K_{FI}$	$1{,}5 \cdot \psi_0 \cdot K_{FI}$

Table A1.2(B+C) DK NA Design values of actions for persistent and transient design situations (STR/GEO) (sets B and C)

Limit state				STR/GEO				STR
Combination of actions				1	2	3	4	5
Reference formula				(6.10a)	(6.10b)	(6.10a)	(6.10b)	(6.10a)
Partial factors for actions								
Permanent action	Weight, general (**)	Unfavourable	$\gamma_{G;sup} \cdot K_{FI}$	$1{,}2 \cdot K_{FI}$	$1{,}0 \cdot K_{FI}$	1,2	1,0	1,0
		Favourable	$\gamma_{G;inf}$	1,0	0,9	1,0	0,9	1,0
	Weight of soil and (ground) water, geotechnical structures (***)	Unfavourable	$\gamma_{G;sup}$	1,0	1,0	1,0	1,0	1,0
		Favourable	$\gamma_{G;inf}$	1,0	1,0	1,0	1,0	1,0
Variable action (*)	Leading	Unfavourable	$\gamma_{Q,1} \cdot K_{FI}$	0	$1{,}5 \cdot K_{FI}$	0	1,5	0
	Other	Unfavourable	$\gamma_{Q,i} \cdot K_{FI}$	0	$1{,}5 \cdot \psi_0 \cdot K_{FI}$	0	$1{,}5 \cdot \psi_0$	0
Structural materials, cf. EN 1992 - 1996 and 1999			γ_0	1,0	1,0	K_{FI}	K_{FI}	$1{,}2\ K_{FI}$
Soil parameters and resistance, cf. EN 1997-1				1,0	1,0	K_{FI}	K_{FI}	1,0 ($\gamma_M = \gamma_R = 1{,}0$)

Example – 'direct' calibration of partial factors

Limit state equation:

$$g = zR - G - Q$$

z design variable
R resistance
G permanent load
Q variable load

	Distribution	Expected value	Coefficient of variation
R	Lognormal	1 kN/m²	0.15
G	Normal	2 kN	0.1
Q	Gumbel	3 kN	V

Target reliability index: β_t=3.8 and V=0.4:
z=15.6 m² and β-point: $(r^*, g^*, q^*) = (0.76,\ 2.04,\ 9.83)$.

Characteristic values:
R 5 % quantile: r_c=0.77
G 50 % quantile: g_c=2.0
Q 98 % quantile:

$$q_c = \mu_Q\left(1 - V\frac{\sqrt{6}}{\pi}[0.5772 + \ln\{-\ln(0.98)\}]\right) = 2.04\mu_Q = 6.12$$

Example – 'direct' calibration of partial factors

Partial factors:

$$\gamma_R = \frac{r_c}{r^*} = \frac{0.77}{0.76} = 1.01$$

$$\gamma_G = \frac{g^*}{g_c} = \frac{2.04}{2.0} = 1.02$$

$$\gamma_Q = \frac{q^*}{q_c} = \frac{9.83}{6.12} = 1.61$$

Partial safety factors obtained by reliability-based calibration:

β_t	V	γ_R	γ_G	γ_Q
3.8	0.2	1.10	1.04	1.28
4.3	0.2	1.13	1.04	1.43
4.8	0.2	1.18	1.04	1.60
3.8	0.3	1.04	1.02	1.47
4.3	0.3	1.08	1.02	1.68
4.8	0.3	1.12	1.02	1.91
3.8	0.4	1.01	1.02	1.61
4.3	0.4	1.05	1.02	1.84
4.8	0.4	1.10	1.02	2.12

Example – calibration by Design value format method

Design value x_d : $F_X(x_d) = \Phi(-\alpha\beta')$

$F_X(x)$ distribution function for stochastic variable X

Example: β'=3.8

For strength variables: α= 0.8

For dominating loads: α= -0.7

For non-dominating loads: α= -0.4 x 0.7 = -0.28

Characteristic value x_c : $F_X(x_c) = 0.05$

Partial safety factors:

$\gamma = \theta \frac{x_c}{x_d}$ strength variables

$\gamma = \theta \frac{x_d}{x_c}$ load variables

θ uncertainty factor, typically = 1.05

x_c characteristic value

Example - calibration by Design value format method

Recommended distribution types:

For permanent loads: Normal distribution:

$$x_d = \mu_X (1 + 0.7\beta' V)$$

$x_c = \mu_X$ mean value

For variable loads: Gumbel distribution:

$$x_d = \mu_X \left(1 - V \frac{\sqrt{6}}{\pi} \left[0.5772 + \ln\{- \ln(\Phi(0.7\beta'))\} \right] \right)$$

$$x_c = \mu_X \left(1 - V \frac{\sqrt{6}}{\pi} \left[0.5772 + \ln\{- \ln(0.98)\} \right] \right)$$

98% quantile

For strength: Lognormal distribution:

$$x_d = \mu_X \exp(-0.8\beta' V)$$

$$x_c = \mu_X \exp(-1.64 V)$$

5% quantile

Example - calibration by Design value format method

Partial safety factors obtained using the design value method:

β_t	V	γ_R	γ_G	γ_Q	$\beta(\gamma_R, \gamma_G, \gamma_Q)$
3.8	0.2	1.22	1.27	1.16	4.19
4.3	0.2	1.28	1.30	1.28	4.67
4.8	0.2	1.38	1.34	1.40	5.25
3.8	0.3	1.22	1.27	1.21	4.03
4.3	0.3	1.28	1.30	1.36	4.50
4.8	0.3	1.38	1.34	1.52	5.08
3.8	0.4	1.22	1.27	1.25	3.90
4.3	0.4	1.28	1.30	1.42	4.39
4.8	0.4	1.38	1.34	1.60	4.94

Reliability level – DK National Annex

ULS 1 year reference period

CC2

NKB: 1975 $\beta = 4.3$ (loads: Normal distributed)

JCSS $\beta = 4.2$

EN 1990:2002 $\beta = 4.7$

DS 409:1998 $\beta = 4.8$

EN 1990 Nat. Annex $\beta = 4.3$

JCSS PMC (2002):

Relative cost of safety measure	Minor consequences of failure	Moderate consequences of failure	Large consequences of failure
High	3.1	3.3	3.7
Normal	3.7	4.2	4.4
Low	4.2	4.4	4.7

DK National Annex

Design value for resistance

Model 1

$$R_d = \frac{R(X_d, d_d)}{\gamma_R}$$

$R(X,d)$ calculation model for resistance R as function of strength parameters X and geometry d
γ_R partial factor related to uncertainty in calculation model (model uncertainty)
d_d design value of geometrical parameters
X_d design value of strength parameters

Design value of the strength parameter, X_d :

$$X_d = \eta \frac{X_k}{\gamma_m}$$

η modification factor for e.g. load duration, temperature and scale effects
X_k characteristic value of strength parameter
γ_m $= \gamma_4$: partial factor for strength parameter

$$\gamma_R = \frac{\gamma_1 \gamma_2 \gamma_3}{b}$$

γ_1 depends on type of failure (with or without warning)
γ_2 depends on the uncertainty related to the calculation model
γ_3 partial factor dependent on the scope of checking in connection with the production of components and execution at the construction site
b bias (additional safety) related to the calculation model

DK National Annex

Design value for resistance

Model 2

$$R_d = \eta \frac{R_k}{\gamma_M}$$

η modification factor for e.g. load duration, temperature and scale effects
R_k characteristic value of resistance determined by
$R_d = R(X_k, d_d)$
γ_M partial factor determined by

$$\gamma_M = \frac{\gamma_1 \gamma_3 \gamma_4}{b}$$

Model 3

$$R_d = \eta \frac{R_k}{\gamma_M}$$

η modification factor for e.g. load duration, temperature and scale effects
R_k characteristic value of resistance determined by tests
γ_M partial factor determined by

$$\gamma_M = \gamma_1 \gamma_3 \gamma_4$$

DK National Annex

Uncertainty and partial factors

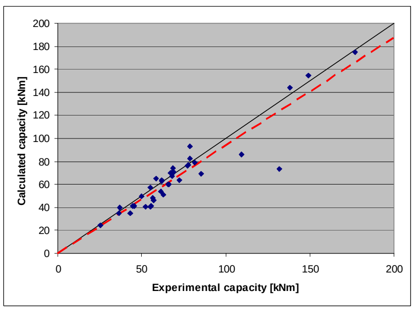
	Strength parameter +	Computational model →	Load bearing capacity
Uncertainty	$V_m = \sqrt{V_{m0}^2 + V_{mp}^2}$	$V_2 = \sqrt{V_{20}^2 + V_{2p}^2}$	$V_M = \sqrt{V_m^2 + V_2^2}$
Partialfactor	γ_m	γ_2	$\gamma_M = \gamma_m \gamma_2$

index *0* : uncertainty related to production test data / laboratory tests

index *p*: uncertainty related to difference between production / laboratory conditions and real structure

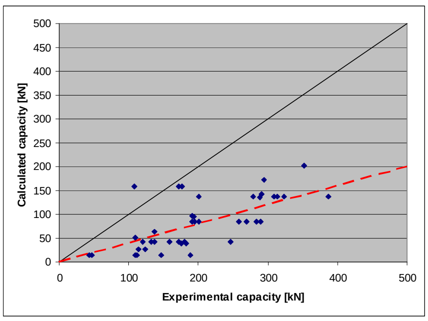
DK National Annex

Computational model uncertainty - examples



small bias: 1.06

small COV: V_{20} =12%



large bias: 2.5

large COV: V_{20} =25%

DK National Annex
Calibration material partial factors

Representative limit state equation:

$$g = zR - ((1-\alpha)G + \alpha Q)$$

z	design parameter
R	resistance: LogNormal
G	permanent load: Normal: COV = 10%
Q	annual max variable action: Gumbel: COV = 40%
α	parameter between 0 and 1

DK National Annex
Calibration material partial factors

Design equation:

(6.10a): $G = z_a \dfrac{R_k}{\gamma_M} - ((1-\alpha)\gamma_{Ga} G_{Uk}) = 0$

(6.10b): $G = z_b \dfrac{R_k}{\gamma_M} - ((1-\alpha)\gamma_{Gb} G_k + \alpha \gamma_Q Q_k) = 0$

$$z = \max\{z_a, z_b\}$$

$$\gamma_{Ga} = 1.2$$

$$\gamma_{Gb} = 1.0$$

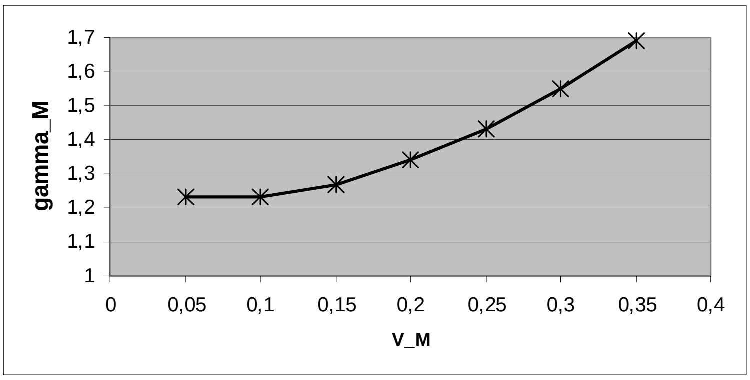
$$\gamma_Q = 1.5$$

NB: no bias included

DK National Annex

Calibration material partial factors

Partial factor γ_M is calibrated to the reliability index $\beta = 4.3$



DK National Annex

Table F.1 DK NA Sub-partial factor γ_4 for measured strength parameter or resistance

Coefficient of variation for measured strength parameter or resistance	≤ 5 %	10 %	15 %	20 %	25 %	30 %
γ_4	1,15	1,20	1,25	1,30	1,35	1,40

Table F.3 DK NA Sub-partial factor γ_2 for uncertainty of the calculation model

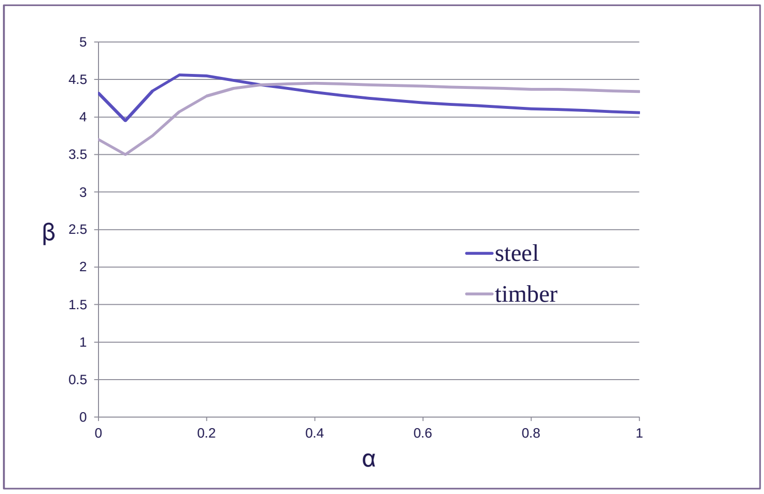
Coefficient of variation of the calculation model	≤ 5 %	10 %	15 %	20 %	25 %
γ_2	1,05	1,10	1,15	1,20	1,25

Table F2 DK NA Sub-partial factor γ_1 depending on type of failure

Type of failure	Warning of failure with residual re-sistance	Warning of failure without residual re-sistance	No warning
γ_1	0,90	1,00	1,10

DK National Annex

Example: 'Annual' reliability index:



Concluding remarks - challenges

- More information on the determination of γ_M and γ_R partial factors dependent upon strength parameters and calculation models
- Target reliability level:
  - Annual or lifetime?
  - Cost of safety measure
  - Existing structures
- Solve the 'paradox' problem for EQU – STR load combinations
- Develop a consistent basis for accounting for 'hidden' safety - bias - in calculation models for action effects (and resistances)
- Partial factors for fatigue accounting for uncertainty of fatigue loads and of inspections

AALBORG UNIVERSITY
DENMARK

Thank you for your attention!

John Dalsgaard Sørensen
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TNO innovation for life

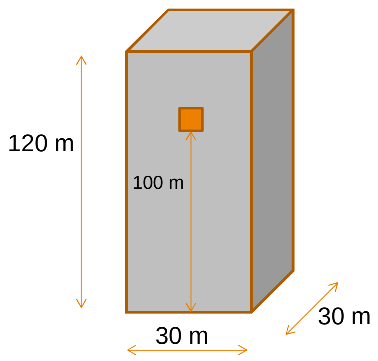
Reliability analysis of a façade element under wind loading

prof.dr.ir. Raphaël Steenbergen

Content presentation

- Design according to EN 1991-1-4 and EN 1990
- Reliability analysis of this design, full probabilistic analysis
  - Distribution function strength
  - statistical properties load parameters: wind stations + wind tunnel
  - model uncertainties
- Evaluation of the resulting reliability

Façade element



Tall building
In city

Façade element 10 m^2

z_0=0.8m

v_b=27m/s

Characteristic wind load on element: EN 1991-1-4

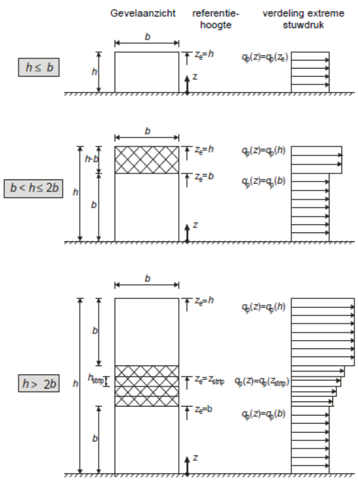
$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z)$$

$$v_m(z) = c_r(z) \cdot c_o(z) \cdot v_b$$

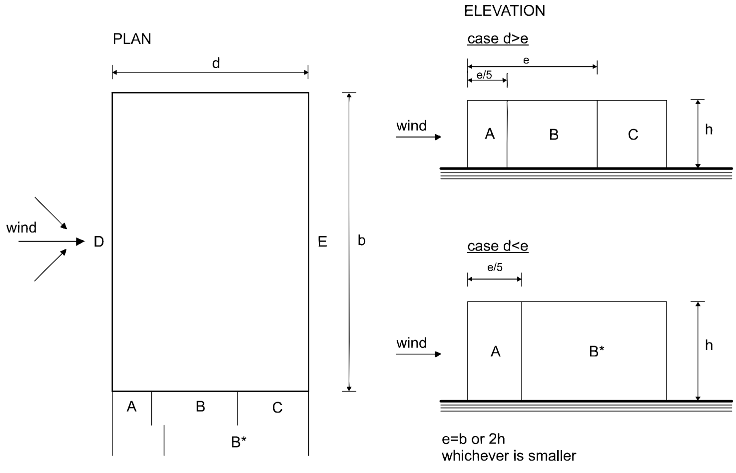
$$c_r(z) = k_r \cdot \ln\left(\frac{z}{z_0}\right) \qquad k_r = 0{,}19 \cdot \left(\frac{z_0}{z_{0,II}}\right)^{0{,}07}$$

$$I(z) = \frac{1}{\ln(z/z_0)}$$

Characteristic wind load on element: EN 1991-1-4



Characteristic wind load on element: EN 1991-1-4



Characteristic wind load on element: EN 1991-1-4

Table 7.2.1: External pressure coefficients for vertical walls of rectangular plan buildings

Zone	A		B		C		D		E	
h/d	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
5	-1,2	-1,4	-0,8	-1,1	-0,5		+0.8	+1,0	-0,7	
1	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,5	
< 0,25	-1,2	-1,4	-0,8	-1,1	-0,5		+0,7	+1,0	-0,3	

Note (i): For intermediate values of h/d, linear interpolation should be used.
Note (ii): The values of table 7.2.1 also apply to walls of buildings with inclined roofs, such as duopitch and monopitch roofs.

For buildings with h/d > 5, the total wind loading may be based on the provisions given in sections 7.6 to 7.8 and 7.9.2.[h1]

(3) In cases where the wind force on building structures is determined by application of the pressure coefficients c_{pe} on windward and leeward side (zones D and E) of the building simultaneously, the lack of correlation of wind pressures between the windward and leeward side may be taken into account. For buildings with $h/d \geq 5$ the resulting force is multiplied by 1. For buildings with $h/d \leq 1$, the resulting force is multiplied by 0,85. For intermediate values of h/d, linear interpolation may be applied.

Characteristic wind load on element: EN 1991-1-4

$$v_{\mathrm{m}}(z = 120\mathrm{m}) = 1.1559 \cdot 27 = 31.2 \text{ m/s}$$

$$I(z) = \frac{1}{\ln\left(z/z_0\right)} = \frac{1}{\ln\left(120/0.8\right)} = 0.20$$

$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) = 1459 \text{ N/m}^2$$

$$F_{W,char} = A \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) \cdot \left[1 + 7 \cdot I_v(z)\right] \cdot c_{pe}$$

$F_{w,char}$ = 10*1459*0.8 =11675 N

Design wind load on element: EN 1991-1-4 & EN 1990

$F_{w,char}$ = 0.8*1459*10 =11675 N

$F_{w,d} = \gamma_W$*11675 = 1.5*11675 = 17512 N
(CC2)

Distribution R

Design according to $R_d = S_d = 17512$ N

R lognormally distributed $V(R)=0.10$

Design according to Eurocode/material factors:

$P(R<R_d)=\Phi(-\alpha\beta)$, with $\alpha=0.8$ and $\beta=3.8$

Distribution R is known

Distribution wind load on façade element

$$S = A\cdot\frac{1}{2}\cdot\rho\cdot v_m^2(z)\cdot\left[1+7\cdot I_v(z)\right]\cdot c_{pe} = A\cdot\frac{1}{2}\cdot\rho\cdot c_r^{\ 2}(z)\cdot v_b^{\ 2}\cdot\left[1+7\cdot I_v(z)\right]\cdot c_{pe}$$

A: deterministic

v_b: distribution yearly maxima hourly averaged wind velocity: from Schiphol Airport (z_0=0.03 m and h=10 m)

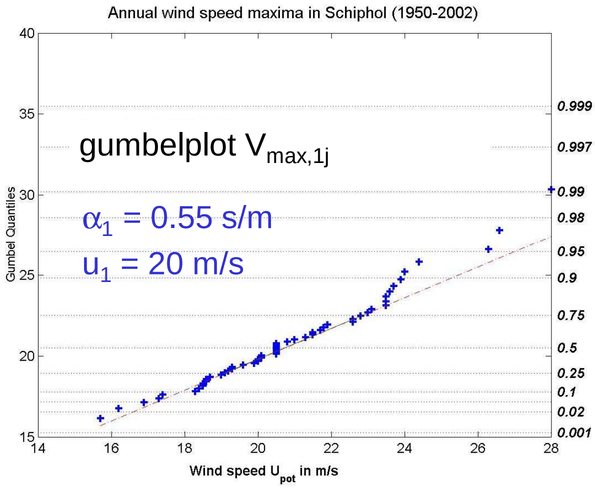
c_r: translation to different roughness and different height: factor from Eurocode (assumed deterministic….)

c_p: peak pressure coefficient: distribution from wind tunnel measurements

Model uncertainties (anemometer, wind tunnel, factors)

TNO innovation for life

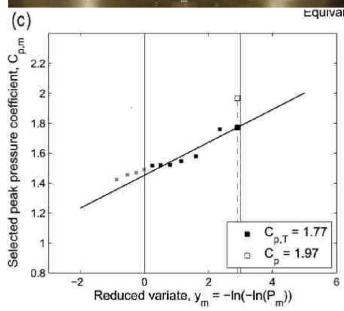
Wind speed



TNO innovation for life

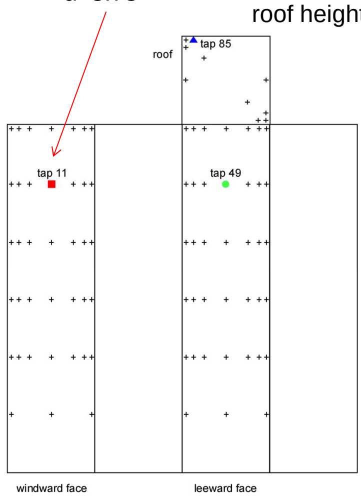
Pressure coefficients

Thanks to Chris Geurts & Okke Bronkhorst



Gumbel:
u_{3600s}=1.64
α=8.78

Related to velocity pressure at roof height



Reliability calculation

$Z = R - m_S S$

$S = 1/2\ \rho\ c_r^2\ v^2\ c_p$

Variable	Distribution	par1	par2
R	Lognormal	$\mu = R_d * \exp(0.8*3.8*0.1)$	V=0.10
R_d	Det	17512 N	
m_S	Normal	$\mu=1.0$	V=0.10
ρ	Det	1.25 kg/m^3	
c_r	Det	1.198	
v	Gumbel	u_{50y}=20+ln50/0.55= 27.1m/s	α=0.55 s/m
c_p	Gumbel	u=1.64	α=8.78

Reliability calculation

Without model uncertainty:

β=2.80, 50 year

With model uncertainty:

β=2.68, 50 year

NB: α_v=0.85!

Reliability sufficient?

EN 1990, CC2: β=3.8

ISO 2394

Target reliability index (life-time) in accordance with ISO 2394.

Relative costs of safety measures	Consequences of failure small	some	moderate	great
High	0	1.5	2.3	3.1
Moderate	1.3	2.3	3.1	3.8
Low	2.3	3.1	3.8	4.3

Dutch National Annex EN 1990: $\beta_{wind} = \beta_{normal} - 1.0$

Reliability sufficient?

In order to satisfy β=3.8:

γ_W=2.15 needed

innovation for life

Conclusions

Reliability assessment on the basis of

wind speed measurements, annual maxima (….fit?)

wind tunnel experiments (sensitivity for sampling time, Cooke, Kasperski, ….)

Hidden safeties captured

Translation to different roughness, wind velocity profile with height

Model uncertainties, use of windtunnel?

JCSS probabilistic model code update

3 calculations: A=1m^2, A=10m^2 (different positions) and global behaviour

Partial factors for wind actions considering time variant and time invariant components

Milan Holický
Czech Technical University in Prague

Wind actions
Wind speed distribution
Partial factors
Conclusions

JCSS/CEN workshop on partial factor for wind actions at TU delft on 17 and 18 February 2015 224

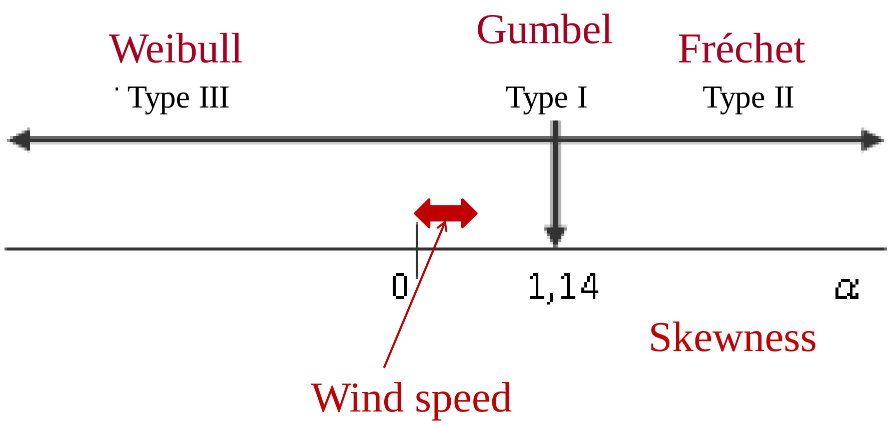
Wind action

- The design wind action considered as a product of time variant and time invariant components

$$w = q\, C = v^2 \frac{\rho}{2} C$$

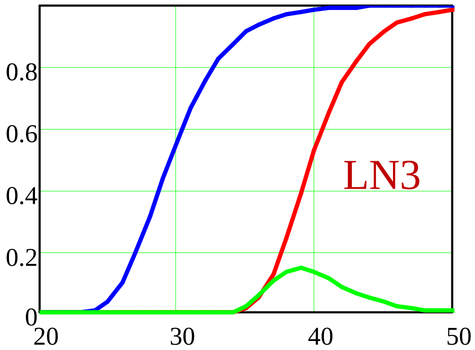
  - Wind speed v described by time variant probability models, Gumbel(μ,σ,1.14) or LN3(μ,σ,α) distribution.
  - Components C described by time invariant normal distribution N(μ,σ).
- Relevant statistical data are needed to improve probabilistic models for both wind speed v and time invariant component C.

Common extreme values distributions



Wind speed v

- Annual extremes (in accordance to available data)
  - The mean $\mu_v \approx 30$ m/s (commonly 25 to 35 m/s)
  - Standard deviation $\sigma_v \approx 3.5$ m/s (commonly 2 to 5 m/s)
  - Skewness $\alpha_v \approx 0.3$ (commonly 0 to 0.5)
- N -years extremes $\Phi_N = \Phi_1{}^N$ for $N = 50$ and LN3
  - The mean $\mu_v \approx 38$ m/s
  - Standard d. $\sigma_v \approx 1.6$ m/s
  - Skewness $\alpha_v \approx 0.6$
- For Gumbel
  - The mean $\mu_v \approx 41$ m/s
  - Standard d. $\sigma_v \approx 3.5$ m/s
  - Skewness $\alpha_v \approx 1.14$



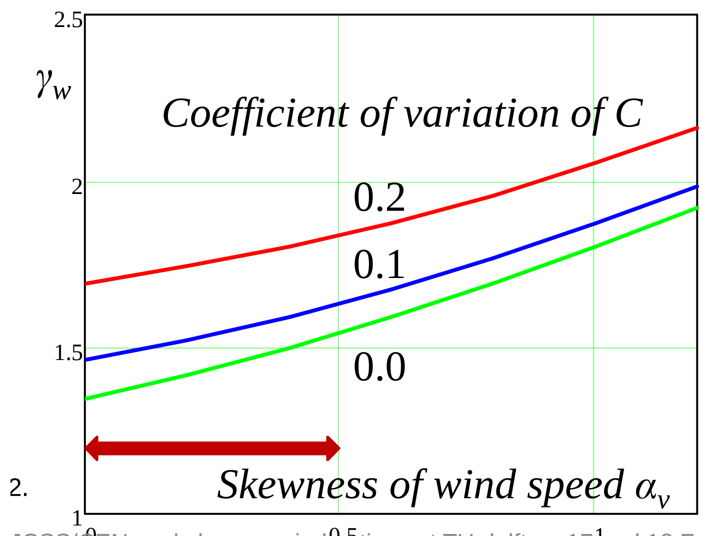
Present study based on LN3

- Wind speed
  - The mean wind speed speed $\mu_{v1} = 30$ m/s
  - The standard deviation $\sigma_{v1} = 3{,}5$ m/s
  - The skewness α_{v1} from 0 to 1.2
- Time invariant component C
  - The mean $\mu_C = 1$ (not affecting the partial factor)
  - The standard deviation $\sigma_C = 0, 0.1, 0.2$
  - The skewness $\alpha_C = 0$

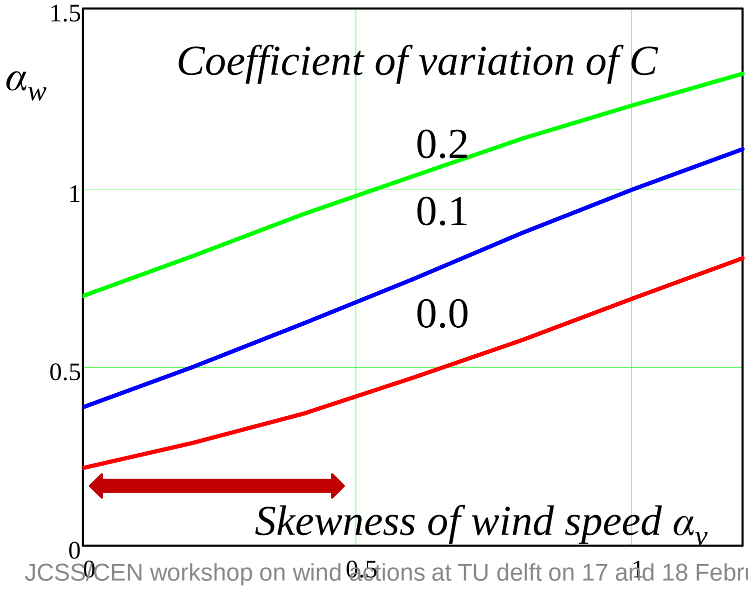
Procedure for determining partial factors

- Parameters of the speed v_1 and C ($w = v^2 \frac{\rho}{2} C$)
- Characteristic wind speed v_k , P($v > v_k$) = 0.98
- Characteristic wind pressure $w_k = v_k^2\ 0.5\ \rho\ \mu_C$
- N years extreme of wind speed v_n, LN3(μ_{vN} ,σ_{vN} , α_{vN})
- Wind pressure w, LN3(μ_w ,σ_w , α_w)
- The design pressure w_d, P($w > w_d$) = $\Phi(\alpha\beta)$, $\alpha = -\ 0.7$
- Partial factor $\gamma = w_d/w_k$, no hiden safety

Wind partial factor γ_w for β = 3.8



Skewness of wind preasure α_w



Approximation using Gumbel distribution

- Wind presure $w = q\ C$
- Time dependent component $q\ = 0{,}5\ \rho\ V^2$
- Time independent component C
- $V_w = (V_q{}^2 + V_C{}^2)^{1/2}$
- An example
- $V_q = 0.168$, $V_C = 0{,}2$, $V_w \cong 0.263$

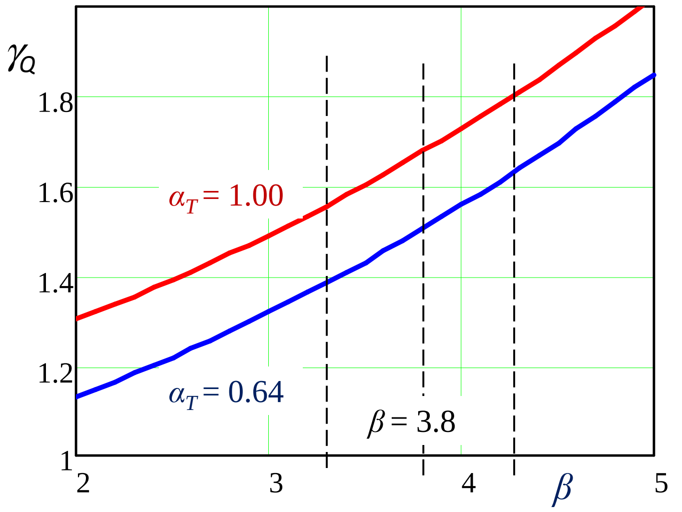
- Time-sensitivity factor
- $\alpha_T = \frac{V_q}{V_w} \cong 0.64$

Partial Factor Method

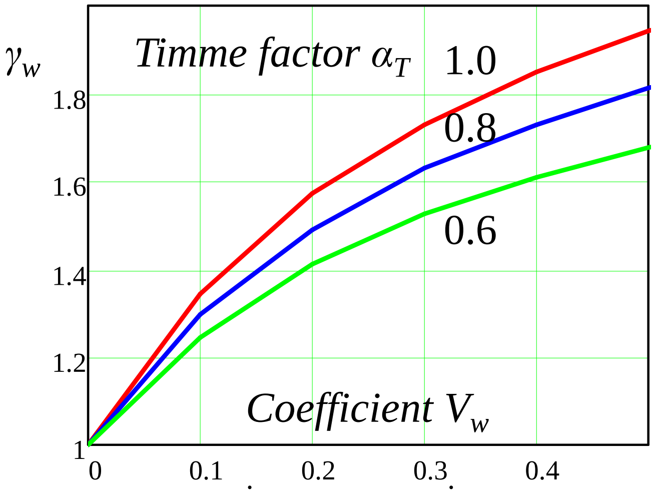
- Gumbel equation modified using time-sensitivity factors to include variability of time invariant components.
  - $\frac{w_k}{\mu} = 1 - V_Q(0.45 + 0.78\ln(-\ln(0.98)))$
  - $\frac{w_d}{\mu} = 1 - V_w\big(0.45 - 0.78\alpha_T \ln(N) + 0.78\ln\big(-\ln\big(\Phi(0.7\beta_T)\big)\big)\big)$
  - $\gamma_Q = \frac{w_k}{w_d}$
  - $\boldsymbol{\alpha_T = \frac{Vw_q}{V_w} \cong 0.64}$

Partial Factor γ_Q

Gumbel distribution, $V_w = 0.263$, $N = 50$ years

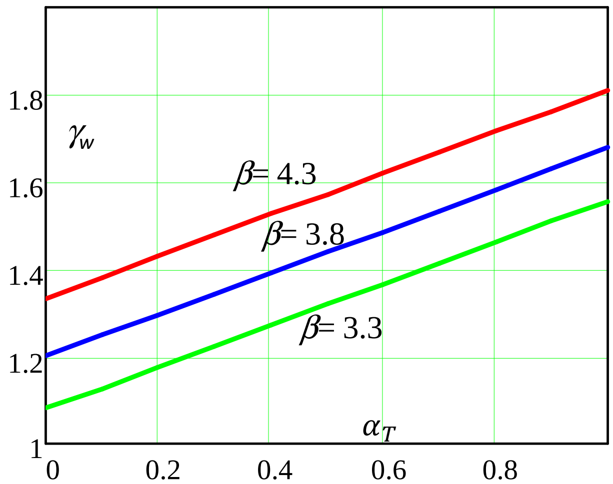


Approximation for β = 3.8



Partial Factors γ_Q for selected β

Variation with α_T for V_w= 0.263, N = 50 years, Gumbel distribution

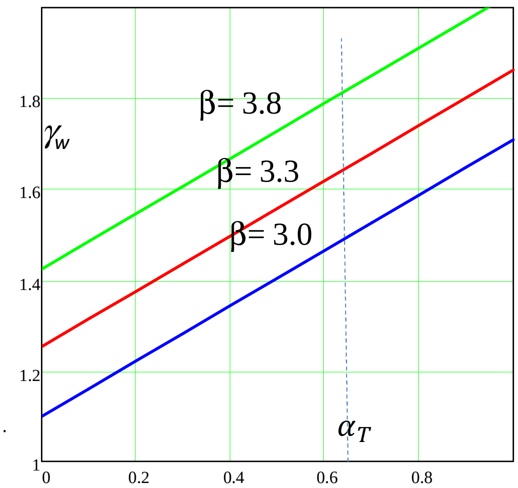


Conclusions

- Wind partial factors depend on both time variant and time invariant components, in particular on
  - skewness of wind speed and
  - Dispersion of time independent components
- Partial factors could be differentiated depending on local wind speed data and type of structures
- In common cases (for $\alpha = -0.7$, $\beta = 3.8$) partial factors γ_w from 1.5 to 1.8 seem to adequate
- Additional relevant data to improve the probabilistic models for wind actions are needed.

Partial Factors γ_Q for selected β

Variation with α_T for $V_w = 0.41$, $N = 50$ years, Gumbel distribution



Mathcad sheet
Wind Factors

MATHCAD sheet "Wind factors" based on three parameter log-normal LN(μ,σ,α) and normal N(μ,σ) = LN(μ,σ,0) distribution

A. Three parameter lognorm distribution including the case when α = 0 (normal distribution) is specified by three moment parameters μ, σ and α .

1. Parameter C and skewness α: $\alpha := -1, -0.9 .. 2$ Check:

Distribution parameter C given by the skewness α: $C(\alpha) := \frac{\sqrt[3]{\left(\sqrt{\alpha^2+4}+\alpha\right)} - \sqrt[3]{\sqrt{\alpha^2+4}-\alpha}}{\sqrt[3]{2}}$ $C(0) = 0$

Distribution bound x0 (μ - 6 σ for zero α): $x0(\mu,\sigma,\alpha) := \begin{cases} \mu - \frac{\sigma}{C(\alpha)} & \text{if } \alpha \neq 0 \\ (\mu - 6\sigma) & \text{otherwise} \end{cases}$ $x0(0,1,0) = -6$

2. Transformation to the standardized normal distribution Φ(u) (for any α):

Standardised variabl: $u(x,\mu,\sigma) := \frac{(x-\mu)}{\sigma}$ Transformed standardised variable:

$$uu(x,\mu,\sigma,\alpha) := \begin{cases} \frac{\ln\left(\left|u(x,\mu,\sigma) + \frac{1}{C(\alpha)}\right|\right) + \ln\left(|C(\alpha)|\cdot\sqrt{1+C(\alpha)^2}\right)}{\text{sign}(\alpha)\cdot\sqrt{\ln\left(1+C(\alpha)^2\right)}} & \text{if } \alpha \neq 0 \\ u(x,\mu,\sigma) & \text{otherwise} \end{cases}$$

3. Density probability function: $uu(50,50,10,0) = 0$

$$\phi(x,\mu,\sigma,\alpha) := \begin{cases} \frac{\text{dnorm}(uu(x,\mu,\sigma,\alpha),0,1)}{\sigma\cdot\left|u(x,\mu,\sigma) + \frac{1}{C(\alpha)}\right|\cdot\sqrt{\ln\left(1+C(\alpha)^2\right)}} \\ \frac{\text{dnorm}(uu(x,\mu,\sigma,\alpha),0,1)}{\sigma} & \text{otherwise} \end{cases}$$

$\phi(50,50,1,0) = 0.399$

4. Distribution function: $\Phi(x,\mu,\sigma,\alpha) := \text{pnorm}(uu(x,\mu,$ $\Phi(2.06,0,1,0) = 0.98$

Development and calibration of SANS 10160-3: Wind Actions

Presented by: Jacques Botha

On behalf of: Celeste Viljoen
Johan Retief

Relationship: Eurocode & SA Wind Loading

- **EN 1991-1-4:2005.** Eurocode 1: Actions on structures, Part 1-4: General actions – wind actions.

Applied as reference for

- **SANS 10160-3:2011.** South African National Standard. Basis of structural design and actions for buildings and industrial structures. Part 3 Wind Actions.

Adaptation to SA Requirements

Following the selection of EN 1991-1-4 as reference, the following adaptations were applied:

1. **Scope of application**
   - modified to buildings & standard design practice;
     - use of Eurocode beyond SANS scope
2. **Mixed strong wind climate**
   - adjustment for thunderstorms
3. **Terrain roughness**
   - classification & profiles
4. **Calibration**
   - in terms of South African reliability models

1. Scope of Application

- SANS 10160 limited to buildings and similar industrial structures
- Level of application limited to general practice, excluding the need of specialised knowledge (wind engineering, in this case)
  - Sufficient compatibility with EN 1991-1-4 for use of advanced methods within SA environment

Therefore scope of structures for SANS 10160-3:

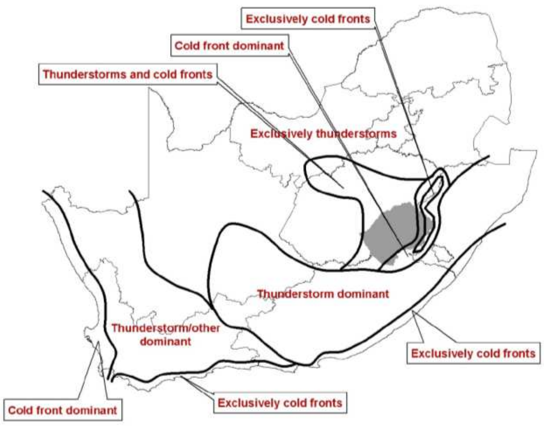
a) Buildings/structures - overall height of up to 100 m

b) elements of buildings and structures having a natural frequency greater than 5 Hz

c) chimneys with circular cross-sections, with heights of less than 60 m and a height to diameter ratio of less than 6,5

2. Strong Wind Climate

- Mixed strong wind climate

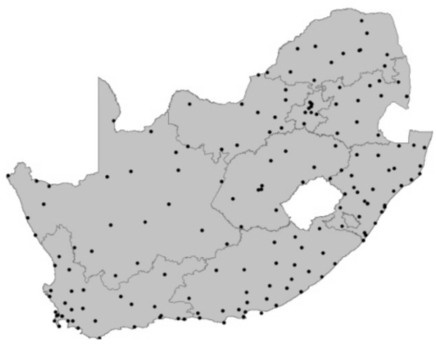


Strong Wind Climate – New Investigations

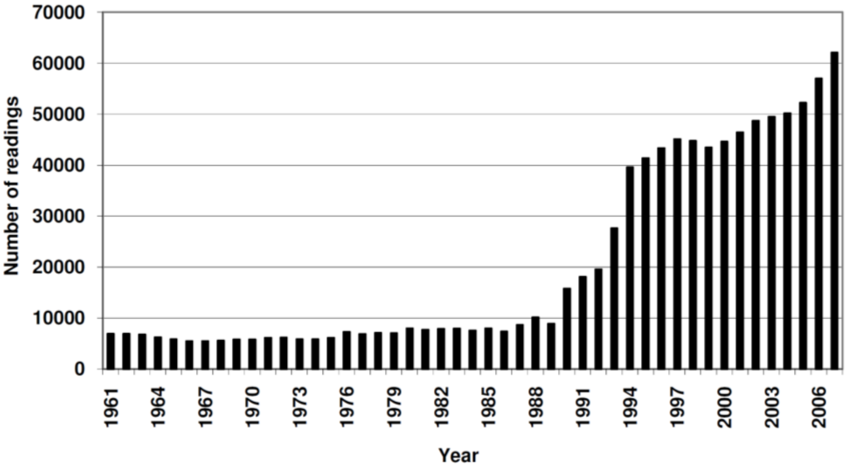
- Updated data records available for weather stations across the country
- Completely updated wind maps for gust wind & hourly mean
  - Mixed climate model used (Gomes and Vickery)
- Final phase of development of revised design wind map (gust)

Spatial Distribution of Weather Stations

- January 1987
- January 2007



Short Data Records



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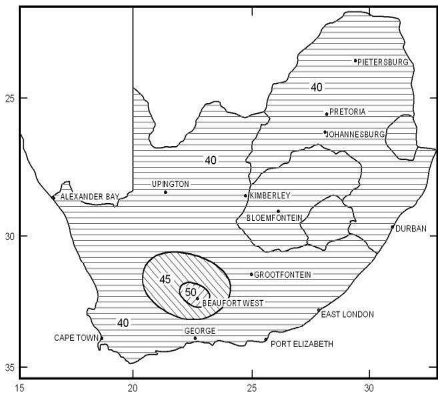
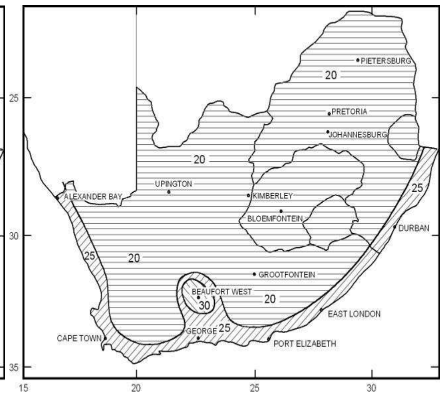
Previous Wind Maps

- Gust wind map
- Hourly mean wind map





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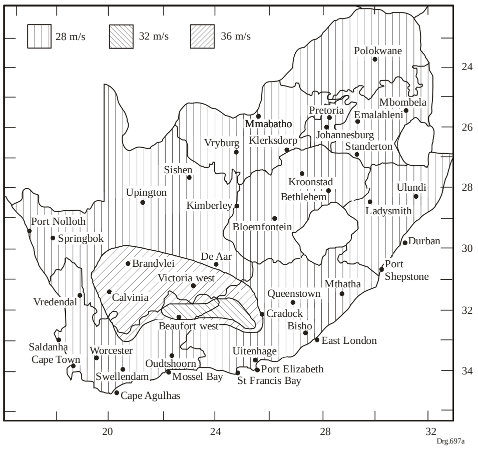
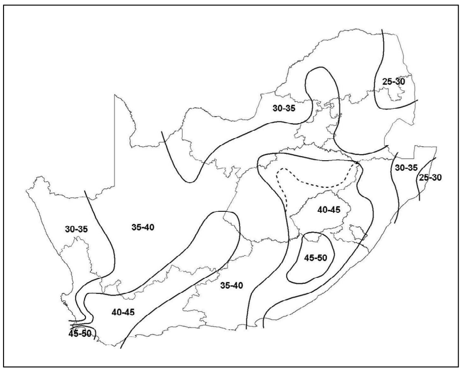
Current Design Wind Map

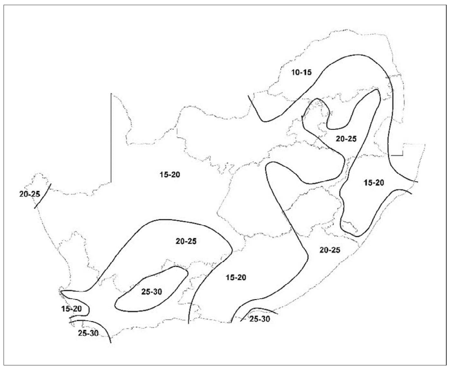
- Gust wind map converted to 10 min mean wind speed map using conversion factor (1,4)



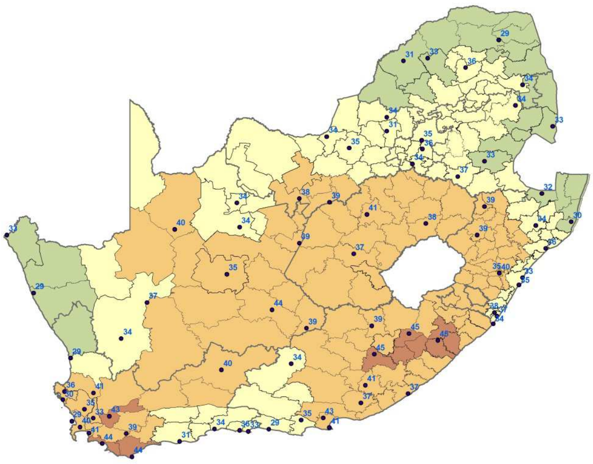
Updated Wind Maps

- Gust wind map
- Hourly mean wind map





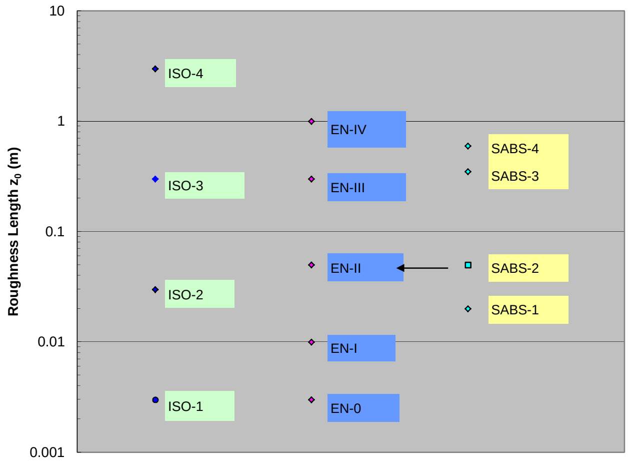
Proposed Updated Design Wind Map (Gust)



3. Terrain Roughness

- Previous SA standard terrain roughness procedures mostly maintained
- EN 1991-1-4 terrain categories were implemented with adjustments:
  - Terrain Category 0 removed
  - SA 1989 roughness lengths (z_0) maintained
- SA 1989 velocity profiles were maintained (power law)
- SA exposure factors lower than Eurocode in few cases

Terrain Roughness Lengths



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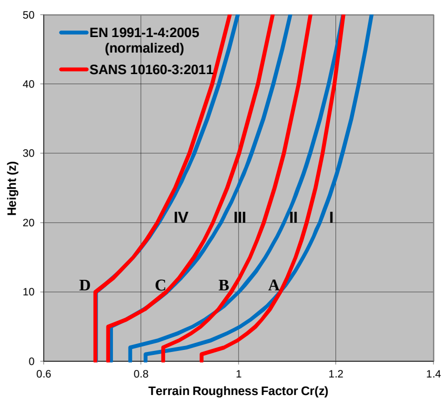
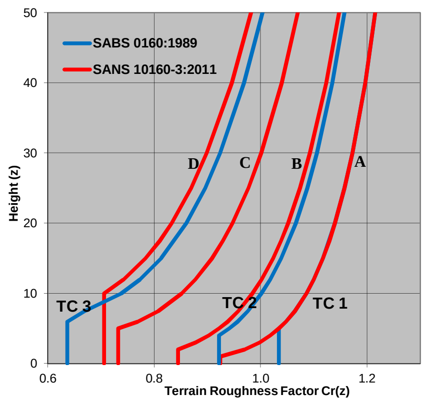
Velocity Profile Comparison

- EN/SANS 2011 comparison
- SANS 2011/SABS 1989 comparison





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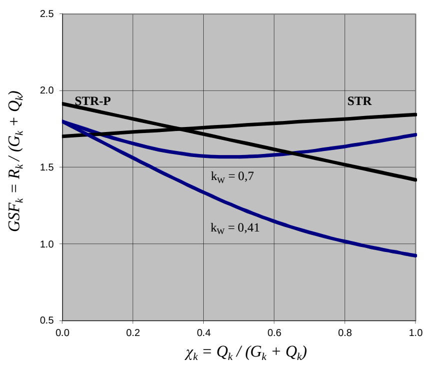
4. Calibration – General

- Generally EN 1-1-4 give significantly higher values than previous SA 1989 procedures
  - Implemented these where convincingly sound
  - Adjusted down otherwise, where related to local conditions, in order to smooth transition from existing practice
- The following measures were taken accordingly, with some interim adjustments:
  - Reflect local strong wind climate,
    - Launch investigation of strong wind climate
  - Maintain terrain roughness representation
  - Implement pressure coefficients resulting higher loads
  - Use existing reliability model & target reliability (β = 3,0)
    - Reassess reliability model

Previous Calibration

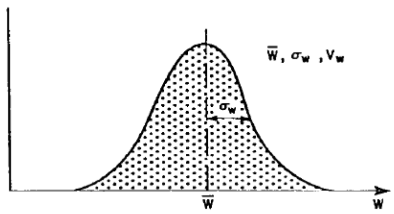
- SANS partial factor for wind actions: γ_W = 1,3
  - Derived from anomalously low value for design wind load bias (k_W) in SANS wind load probability model (0,41)
  - Typical value for k_W = 0,7



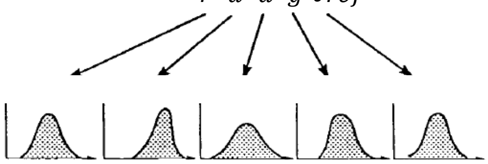
Reliability Model Investigation

- Ongoing investigation
- Investigation overview:
  – Develop new wind load probability model based on transparent reliability data
  – Investigation limited to wind loads on regular industrial buildings
  – Only primary wind load components at the most basic level of approximation are investigated
    - Model uncertainty factors to be investigated at a later stage
  – Global reliability of structures is considered
    - Peak (component and cladding) loads excluded

Total Uncertainty of Wind Loading



$$W = c_r c_a c_d c_g Q_{ref}$$



(Davenport , 1983)

Wind Load Components

- Primary wind load components under investigation:
  - Time variant
    - Free-field wind pressure
  - Time invariant
    - Pressure coefficients
    - Terrain roughness factors
  - Gust factors excluded due to nature of South African free-field wind data

Primary Obstacle

Where to find data to determine the representative probability distributions of the time invariant components?

Investigation Methodology

- Time variant component:
  - New South African free-field wind data and revised wind map
- Time invariant components:
  - Parametric comparative studies of wind load standards
    - EN, SANS, BS NA EN, ASCE, AS/NZS, NBCC, ISO
  - Results from wind tunnel and full-scale tests used to anchor theoretical results to observed values
    - Ex. Texas Tech University full-scale experiments and subsequent related wind tunnel tests

Comparative Study Summary

- Advantages:
  - Allows investigation of wide range of structures and design situations
  - Relatively easy generation of reliability “data” through automation of wind load standard procedures
  - Allows indirect comparison of background information used to develop multiple wind load standards
- Disadvantages:
  - Hidden uncertainties due to wind load standard development procedures
  - Only describes the epistemic component of the wind load uncertainty
  - Not a true estimation of the wind load component uncertainties, but rather a lower bound approximation
  - Useless if not anchored to real world values

Investigation Summary

- Progress:
  - Methods have been developed to determine South African free-field wind probability parameters using new data
  - Wind load standard automation program has been developed
  - Investigation of systematic bias of time invariant components is still ongoing
- Significant Preliminary Results:
  - South African reliability model underestimates total wind load systematic bias
  - Existing models underestimate variability of time invariant wind load components
    - Preliminary terrain roughness CoV: 0,10
    - Preliminary pressure coefficient CoV: 0,25
- Projected completion date is mid-2016

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Thank you