NTNU

Norwegian University of Science and Technology

Wind-induced response of slender suspension bridges:

Full-scale measurements on the Hardanger Bridge

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Introduction

- Interconnected with the E39 project
- Suspension bridges are considered for many connections
- Long-span and super long-span bridges (expensive, credibility at stake)
- Validate models, methods
- How well we can predict the response?
- Unexpected behavior?
- Monitoring of existing structures → good start

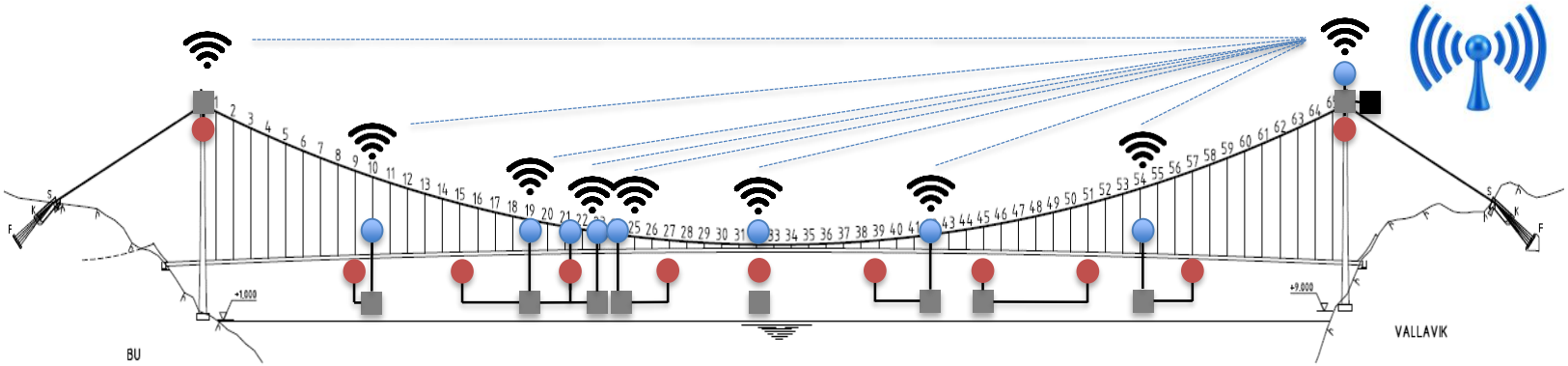
Hardanger Bridge

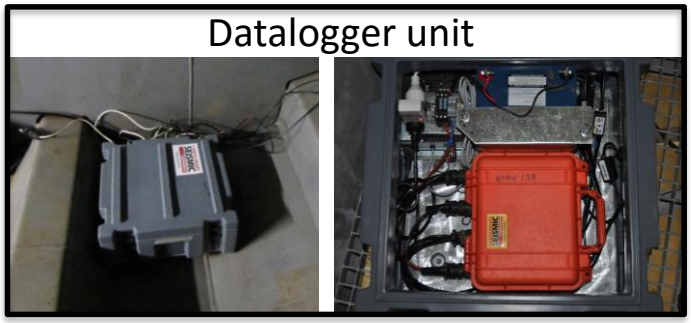
- Opened in 2013 (modern design)
- Main span is 1310 meters (longest in Norway)
- Complex terrain (fjord), Mountains of 1000~1500 m
- Slender deck (18 meters wide)
- Strong winds !

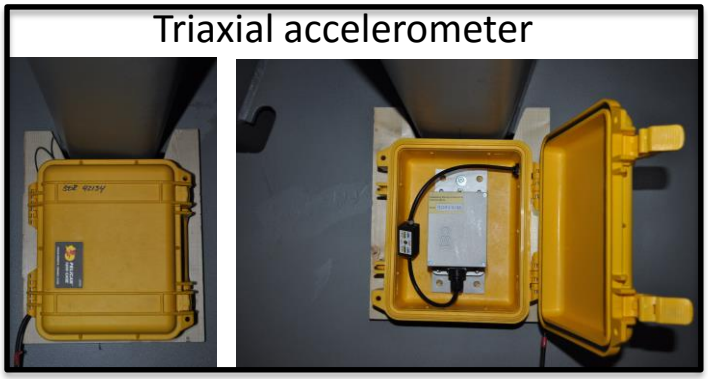
Monitoring wind speeds & accelerations along the bridge!

Measurement System

- 20 accelerometers
- 9 anemometers
- 11 dataloggers
- 10 wireless antennas

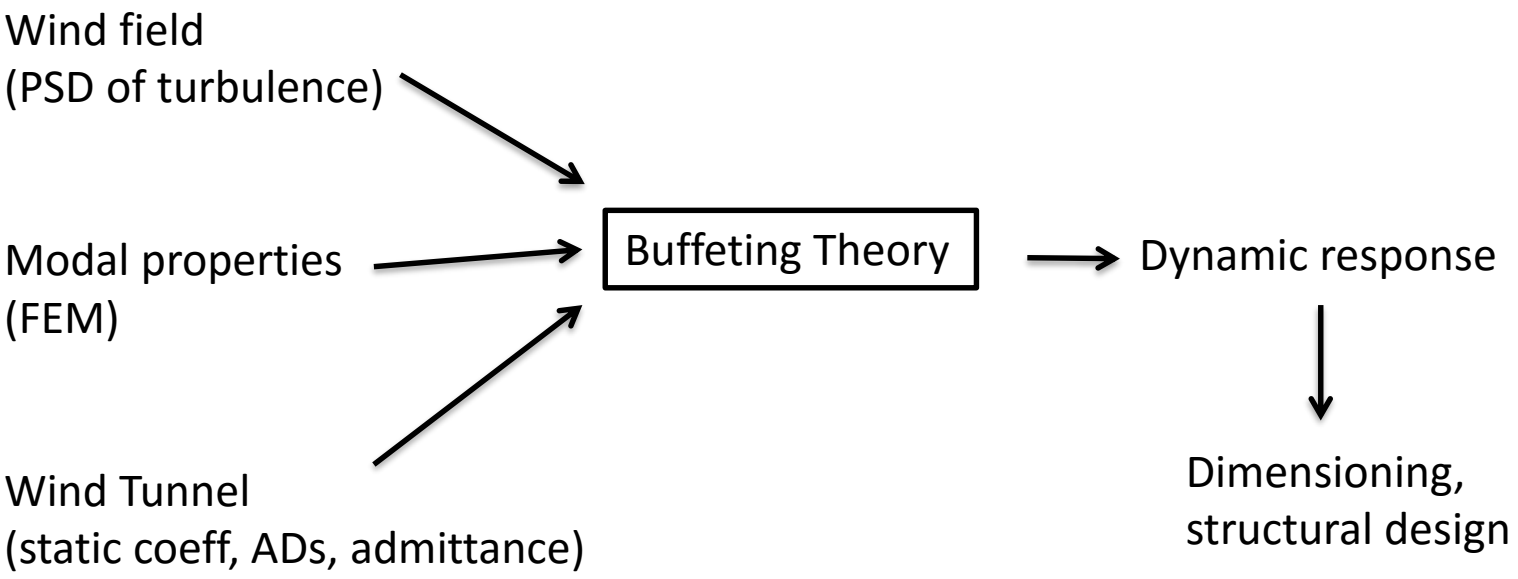






Design of suspension bridges against wind actions

- Buffeting loading



Design of suspension bridges against wind actions

- N400 – Norwegian Handbook for Bridge Design

- Wind Characteristics (for spans > 300 m → field measurements)

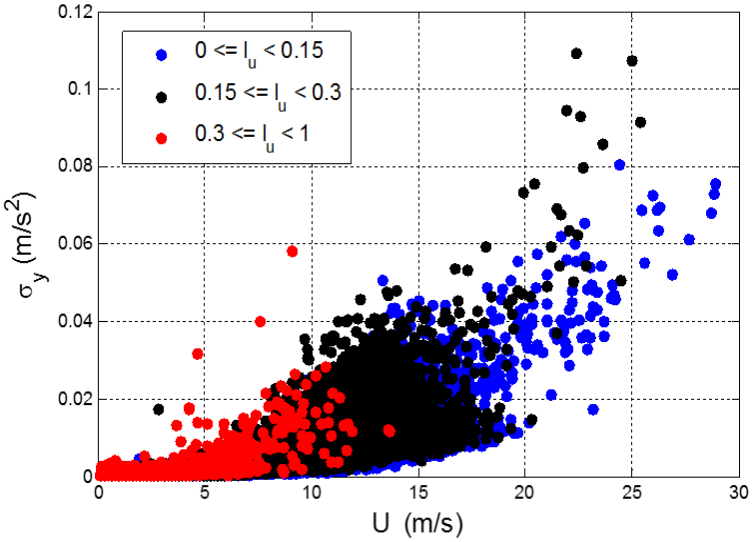
➢ Mean wind speed (design parameter)

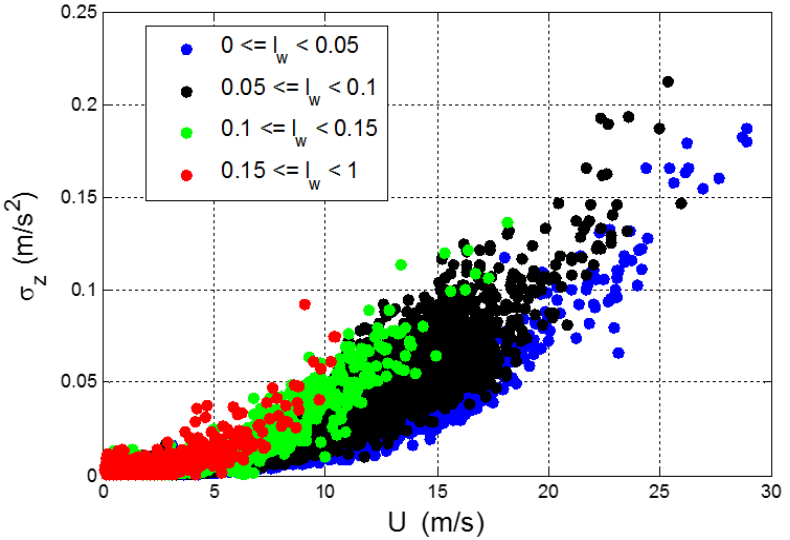
➢ Turbulence intensity
➢ Length scales
➢ One-point spectra
➢ Root coherence

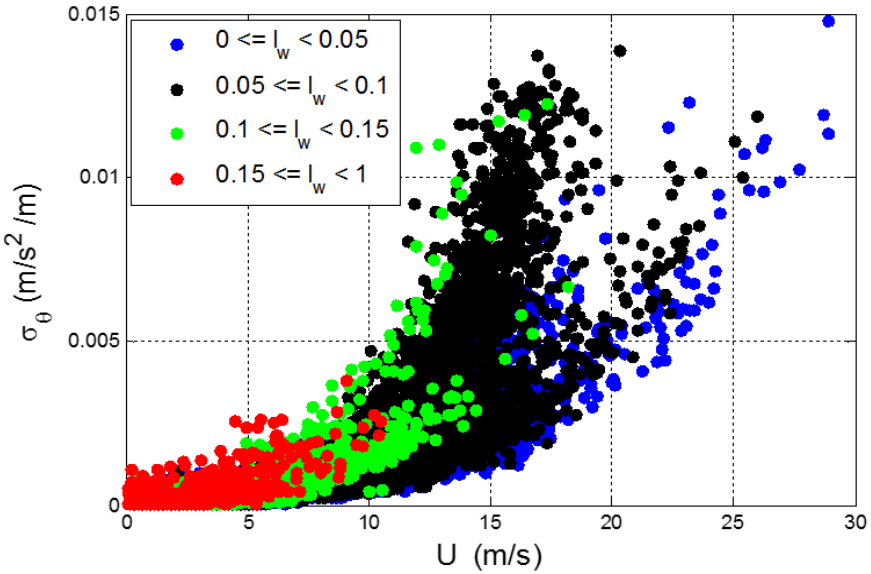
Deterministic!

(functions of height, mean speed)

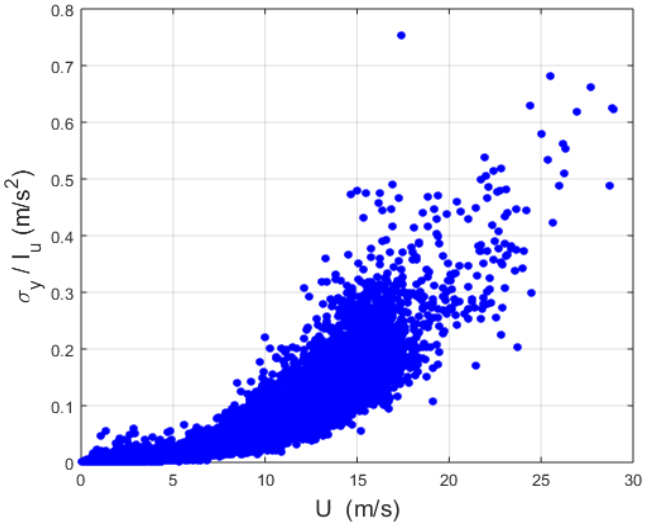
Buffeting Response of the Hardanger Bridge

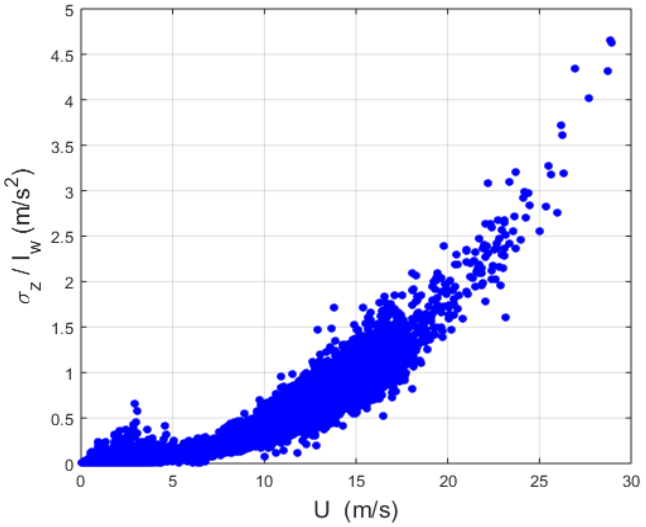


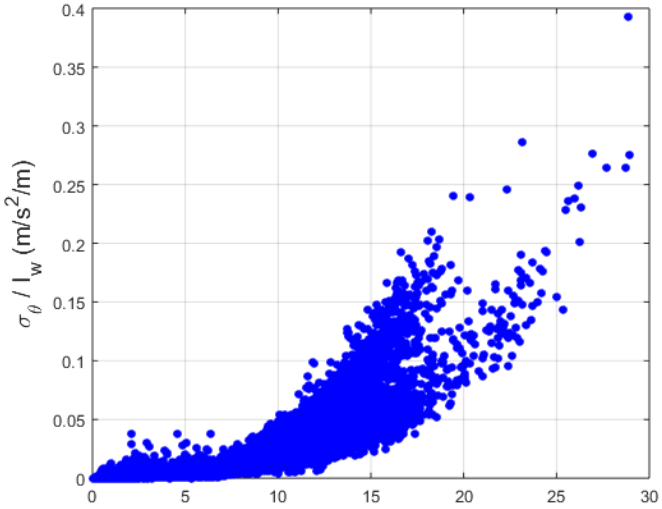




Buffeting Response of the Hardanger Bridge

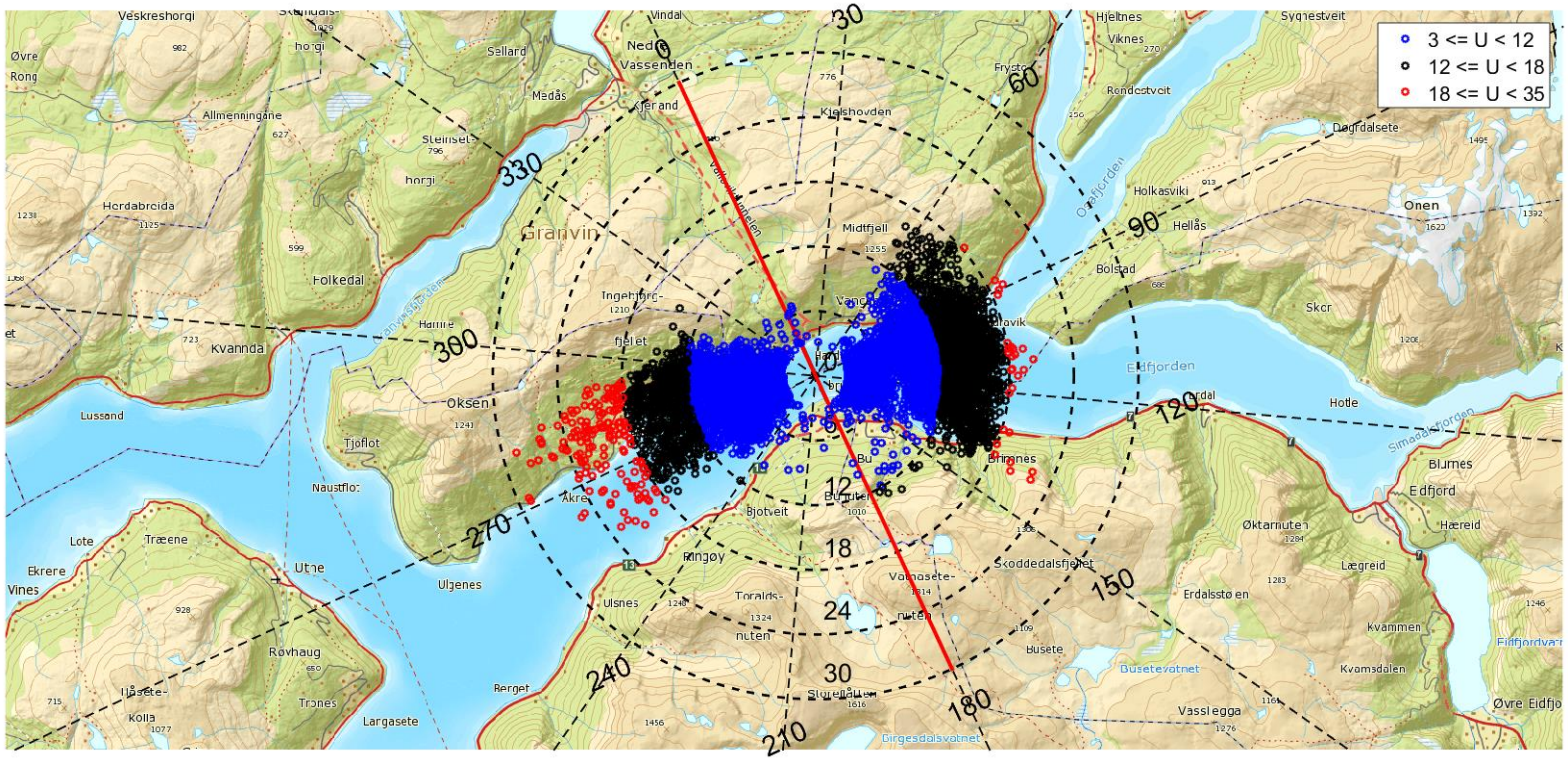






Wind Characteristics

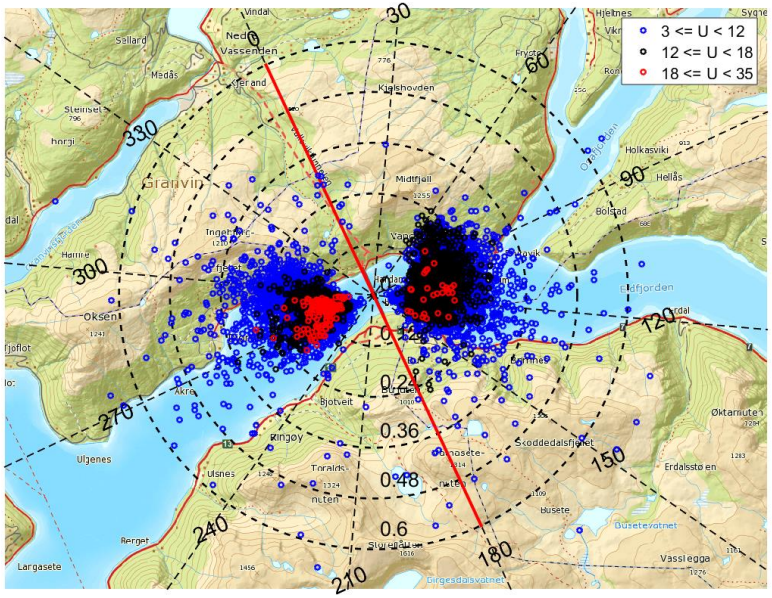
- 10-min mean wind speed (m/s)



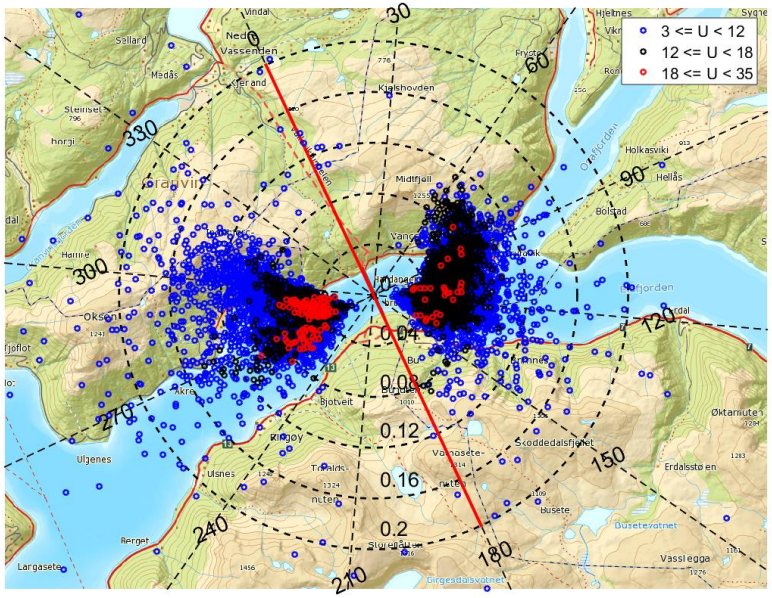
Wind Characteristics

- Turbulence Intensity

Along wind



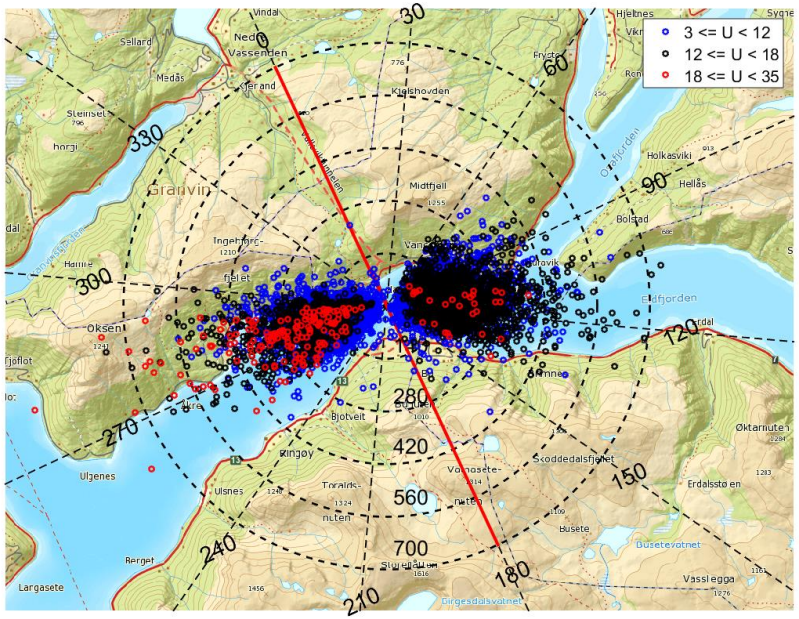
Vertical



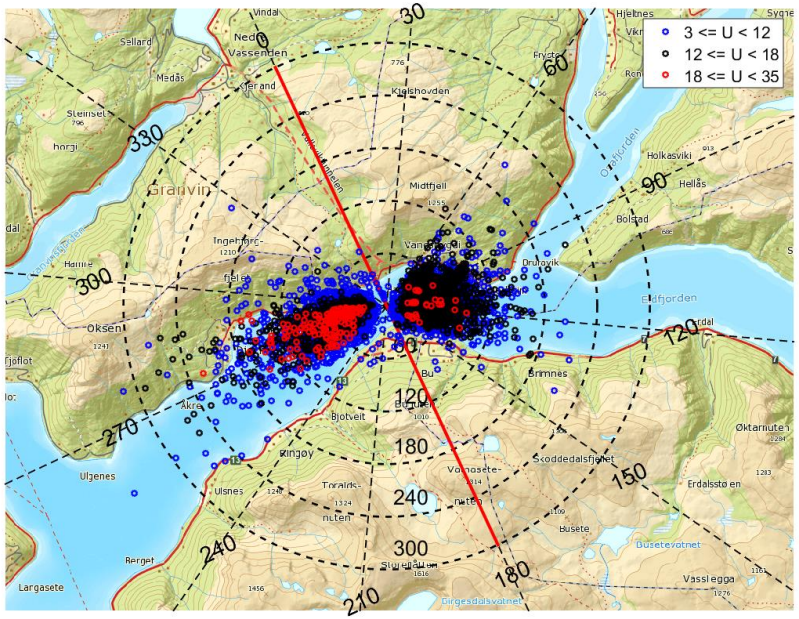
Wind Characteristics

- Length scales (m)

Along wind



Vertical



Response Surface Analysis

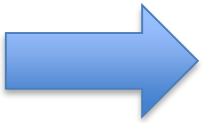
- Linear regression
- Quadratic surface

$$y = \beta_0 + \sum_{i=1}^{n} \left(\beta_i x_i + \sum_{j=i+1}^{n} \beta_{ij} x_i x_j + \beta_{ii} x_i^2 \right)$$

- Estimate coefficients by least squares

Predictor variables:

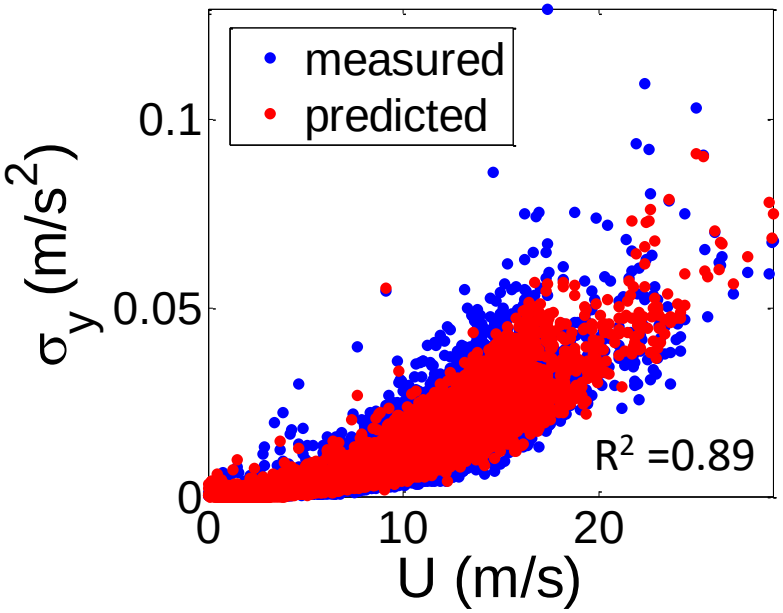
- *mean wind speed (U)*
- *turbulence standard deviations (u,v,w)*
- *length scales (u,w)*
- *wind yaw-angle*
- *angle-of-attack*
- *standard deviation of U along the bridge*

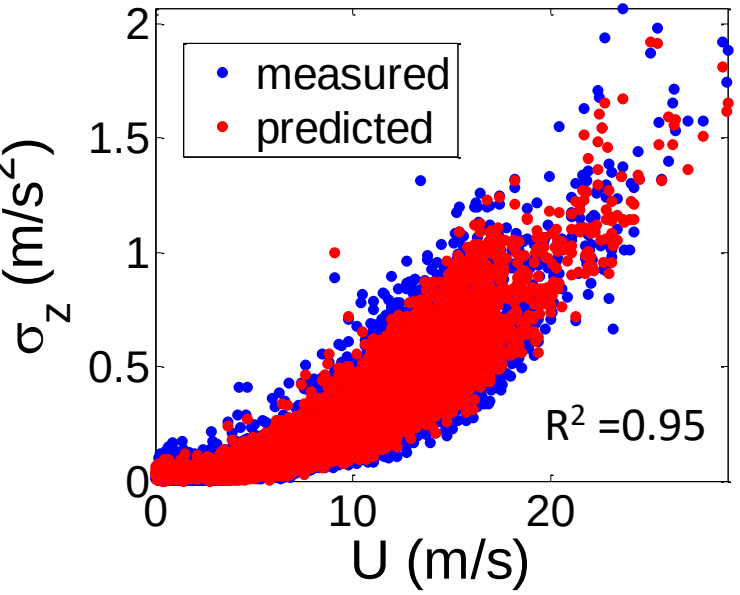


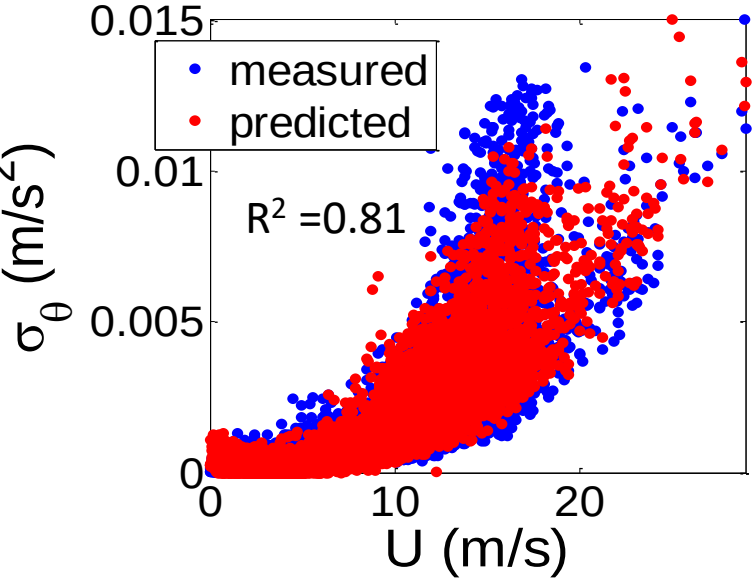
RMS Response

- *Lateral*
- *Vertical*
- *Torsional*

Response Surface Analysis







Response Surface Analysis

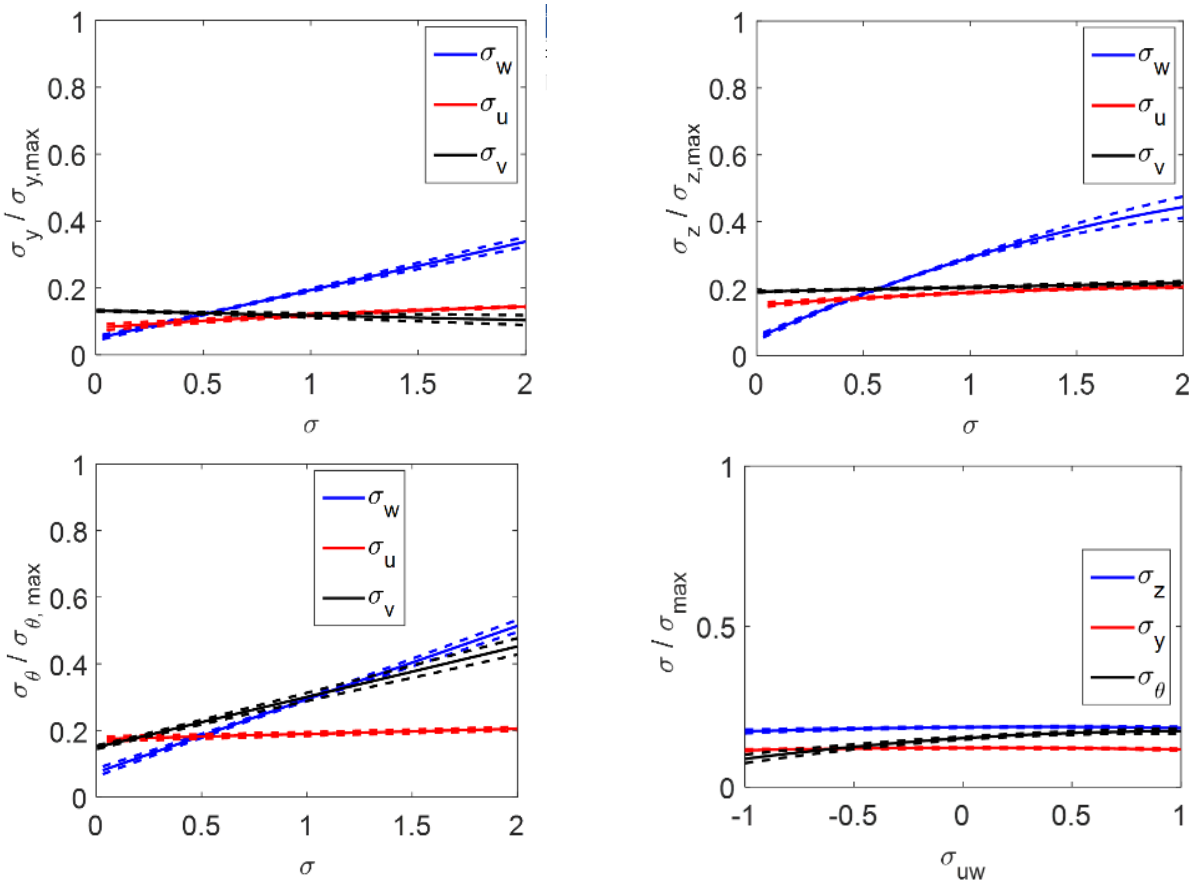
- Importance of wind-related variables: Hypothesis testing (H_0: $\beta = 0$)

Significance of terms in response surface analyses

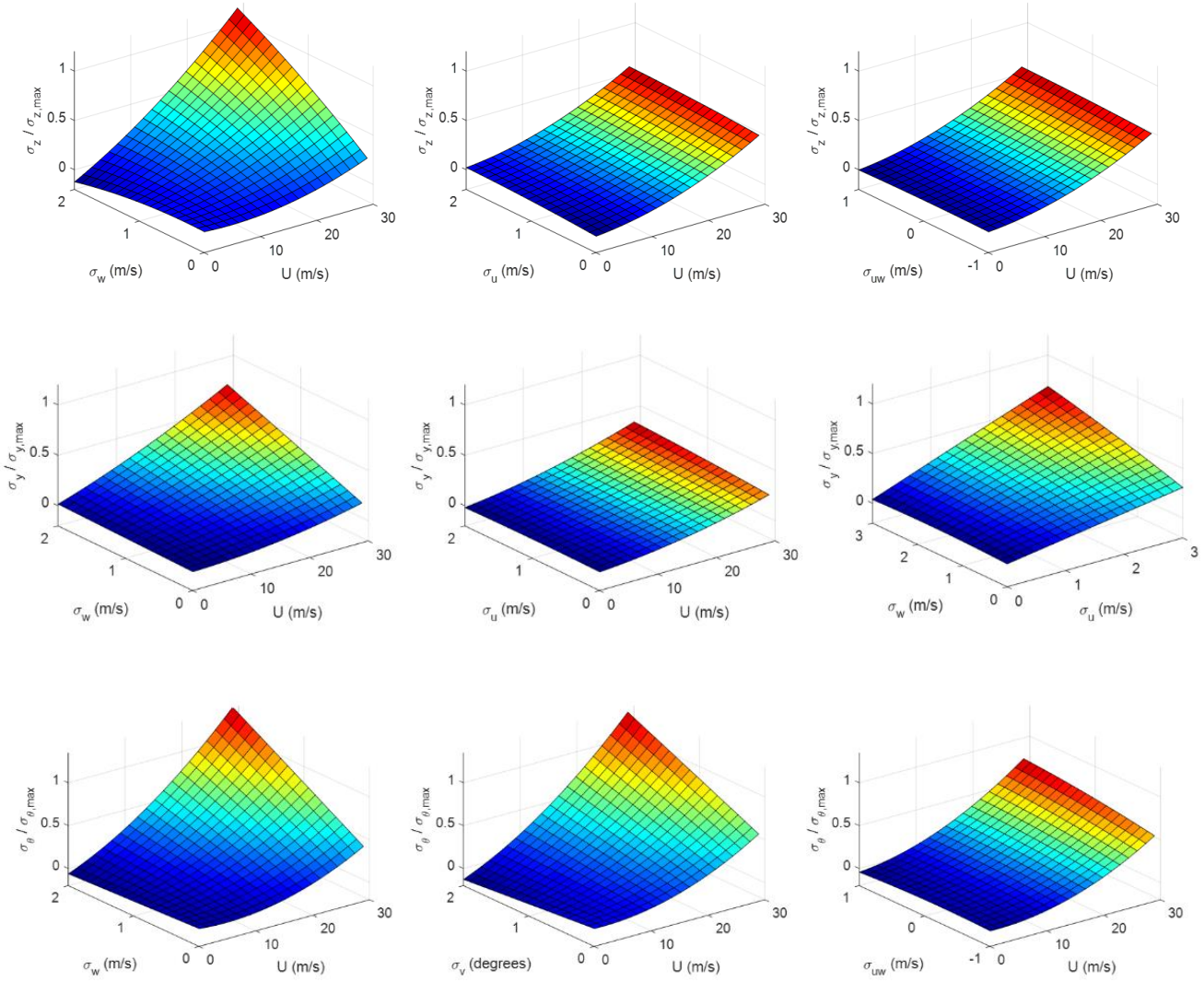
Vertical acceleration		Lateral acceleration		Torsional acceleration	
Term	p-value	Term	p-value	Term	p-value
U	0	$U.\ \sigma_w$	1.96E-58	U	0
$U.\ \sigma_w$	6.85E-214	L_w	3.03E-51	$U.\ \sigma_w$	1.51E-234
U^2	2.60E-137	$\sigma_w.\ \sigma_u$	2.82E-41	$U.\ \sigma_v$	2.49E-169
L_w	9.47E-90	U^2	2.34E-32	U^2	3.08E-147
σ_{ms}	9.01E-48	$\alpha_{yaw}.\ \sigma_u$	2.36E-27	$U.\ \alpha_{yaw}$	5.15E-93
σ_{uw}^2	9.25E-28	$\sigma_w.\ L_w$	7.09E-25	$L_w.\ \sigma_v$	6.76E-67
σ_u	1.01E-26	$\sigma_w.\ \sigma_{ms}$	1.37E-20	$\sigma_w.\ L_u$	3.02E-64
L_w^2	6.27E-21	$\alpha_{yaw}.\ \sigma_v$	2.22E-20	σ_{uw}^2	1.88E-47
$\sigma_w.\ L_u$	1.32E-19	σ_{uw}^2	4.11E-20	α_{yaw}	1.08E-33
$\alpha_{yaw}.\ \sigma_u$	1.23E-17	$U.\ \beta$	9.79E-20	$\alpha_{yaw}.\ L_u$	9.20E-29
$\sigma_w.\ \sigma_v$	4.08E-16	$\sigma_w.\ L_u$	3.09E-17	$U.\ L_w$	7.18E-19
$\sigma_u.\ L_u$	9.53E-16	L_w^2	7.43E-13	$\sigma_u.\ L_w$	8.32E-17
$\sigma_w.\ L_w$	2.90E-15	$\alpha_{yaw}.\ L_u$	1.11E-11	$U.\ \sigma_{uw}$	1.61E-15
σ_u^2	1.64E-13	σ_u^2	2.15E-11	L_w^2	5.62E-15
$\sigma_w.\ \alpha_{yaw}$	2.24E-13	$\sigma_u.\ \sigma_{uw}$	1.43E-10	α_{yaw}^2	4.30E-13
$\sigma_w.\ \sigma_u$	3.14E-13	$U.\ \sigma_u$	5.69E-10	$\sigma_{uw}.\ L_w$	2.04E-12

Response Surface Analysis

- Mean speed → most important (R^2 ~ 60-70%)
- Turbulence



Response Surface Analysis

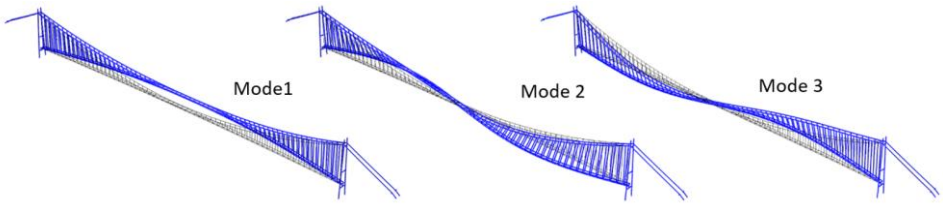


Response Surface Analysis

- Other parameters
- Yaw-angle → similar response levels in skew and perpendicular winds
- Angle-of-attack → no significant correlation is observed
- Length scales → vertical component!

Analytical Prediction of the Buffeting Response

- Multimode theory
- Frequency domain
- Mode shapes from FEM (Abaqus model)

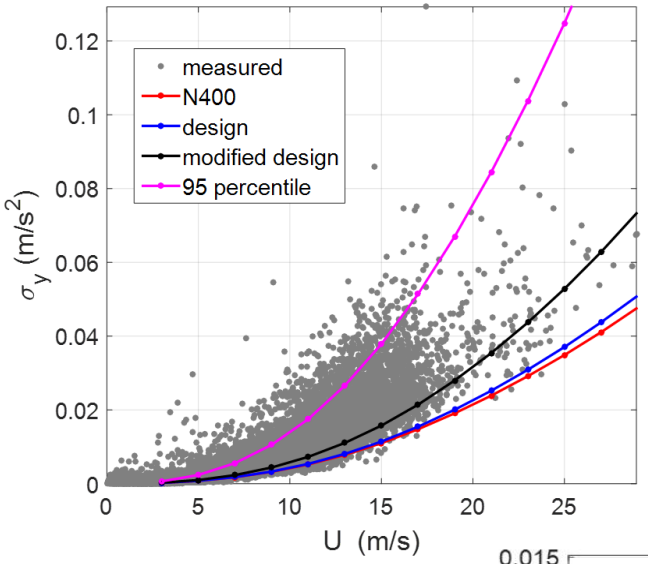


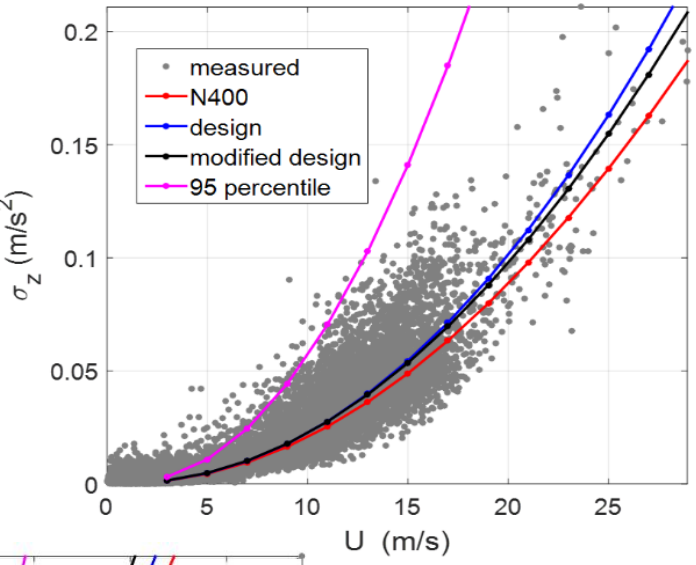
- ADs & static coefficients → wind tunnel tests
- 4 cases

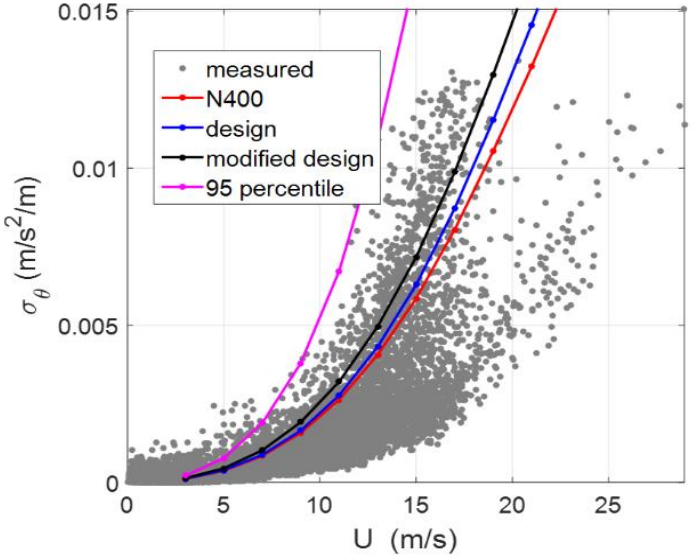
Analytical Prediction of the Buffeting Response

- N400
  - Suggested expressions were used directly
- Design basis
  - N400 adjusted using field measurements
- Modified design
  - Modified using full-scale data
  - Turbulence intensity, one- point spectra, coherence (mean values)
  - Static coefficients corresponding to 3° attack angle
- Conservative
  - 95 percentile values for turbulence intensity & coherence

Analytical Prediction of the Buffeting Response







Conclusions

- Terrain is complex → variable wind conditions
- Observed variability in response doesn't agree with the design methodology
- Variability in response is attributed to the wind field
- Predictions didn't yield satisfactory design curves – why?
- Conservative approach → too conservative
- Eventually → new design approach ?

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Thank you…