EFFECTS OF THE LOCATION OF A BRIDGE ON ITS WIND LOADING.

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Abstract

For the design of a large bridge, the definition of the wind loading is very important. The results of numerical assessments of the bridge behaviour depend very heavily on the wind data. Several parameters come into play, such as the location of the structure, the calculation standards and the assumptions concerning wind modelling. This paper presents the large effects due to some wind assumptions. The conclusions are that contacts with experts in wind engineering are essential.

Keywords: Large bridges, wind engineering, buffeting, wind characteristics, structure location, design standards.

1 Introduction

The study of the behaviour of bridges under the effect of the wind depends of course on the climatic conditions of the region where the bridge is located, but also on the standards and therefore on the way in which the resistance is checked.

In particular, the physical characteristics of the wind are different, for example, in Europe, North America, on the one hand, and Central America, on the other. A partnership between structural engineers and wind engineering experts makes it possible to avoid missing one or other important parameter or to explain the origin of the differences. Having contacts with engineers located in the region where the structure will be built is an asset.

This article presents the differences, sometimes not negligible, obtained according to the standards used and the region where the bridge is built.

The example of a large bridge located in Panama on the Pacific coast, illustrates this point.

No precise information about the bridge is given. The objective is to discuss about a structure subjected to wind loads in different regions of the world and to see the effects of different parameters as:

- The standards used: Eurocode [1] vs AASHTO [2] and AASHTO LRFD Wind Load [3],
- The return period: 700 years vs. 50 years,
- The characteristics of the wind:
  - its spectral density defined with von Karman's or Kaimal's hypotheses
  - its turbulence length scales in the 3 directions of space whose values depend on the Coriolis force and therefore the latitude where the bridge is located

Extremely important factors for the definition of the wind loading are the turbulence length scales that define the size of gusts in all 3 directions. In Europe or North America, the length scale of L_u^x turbulence is about 300 m. But in Central America, it is about 500 to 650 m!

These values affect the power spectral density of wind gusts and their distribution along the bridge.

It concludes that the standards or climate analysis used for the definition of wind load are very important for the design of a structure.

2 Bridge main data's

To illustrate this paper, the project for a large cable-stayed bridge is used as an example. The results must be considered realistic, but the numerical values are indicative. Comparisons are first and foremost qualitative before being quantitative.

The bridge is located in Panama (Fig.1).

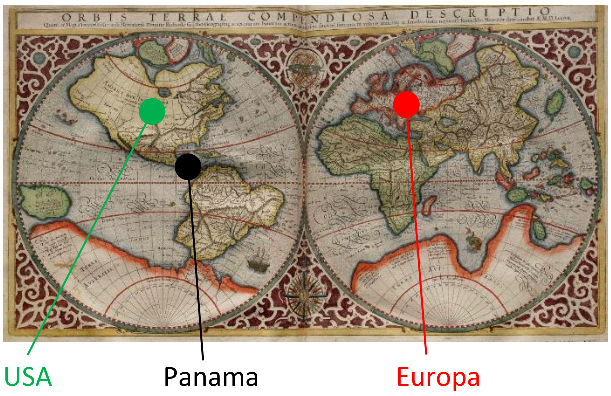


Figure 1 – Mercator's world map

Main bridge data are:

Type of bridge: symmetrical cable-stayed bridge, with a total length of 965 m with a central span of 485 m.

Deck height above the see: 82 m.

Natural frequencies: between 0.1 Hz and 1.0 Hz for the first 20 vibration modes.

Standards: AASHTO [2].

Wind characteristics:

Average speed at 82 m, over 10 minutes with a return period of 700 years = 36.2 m/sec,
Turbulence intensity, I_u(82m) = 12.8 %,
Turbulence length scale, L_u^x = 501 m,
Power Spectral Density: von Karman

3 Design standards - AASHTO vs Eurocode

3.1 Comments

Design standards reflect the state of the art in construction. This state of the art depends on the history of the country or region where the structure is located. In Europe, the Eurocodes bring together the calculation rules; on the American continent, the AASHTO standards are used. These standards define the design assumptions. In addition, project owners may impose one or another standard. In this case, the engineer will have to avoid drawing on one or other standard depending on his calculation habits. A standard is supposed to be consistent with all its rules. This is not necessarily the case from one standard to another.

The first source of wind data in Europe is Eurocode [1] and in the United States, ASCE 7-05/ASCE 7-10 and AASHTO LRDF [3].

The comparison is not obvious insofar as the data are presented in different ways.

3.2 The Return period and safety factor

The first difference concerns the return periods: 50 or 100 years for the Eurocode, for the behaviour in service, SLS, weighted by a safety factor of 1.5 for the ULS and 700 years for the AASHTO, weighted by a safety factor of 1.0 for the verification of resistance.

The wind speed with a return period of 700 years can be obtained with eq. (1).

$$\bar{U}_{TRyears} = \bar{U}_{TR50years} \cdot \left[\frac{1-0.2\ln(\ln(\frac{1}{1-1/TRyears}))}{1-0.2\ln(\ln(\frac{1}{1-0.02}))} \right]^{0.5} \quad (1)$$

$$\text{and } \bar{U}_{TR700years} = \bar{U}_{TR50years} \cdot 1.14$$

3.3 The reference wind speed

3.3.1 For the structure in service

The reference wind speed is the mean speed over 10 minutes for Eurocode, U_{10min}, and the mean speed over 3600 seconds or the maximum speed over 3 seconds, U_{3sec}, for AASTHO.

The DURST [2] curve gives the relation between both definitions.

$$U(t) = 1.277 + 0.296\, x\, th(0.9 x \log(\frac{45}{t})) \qquad (2)$$

$$U_{10\min} = U_{3\sec} / 1.44$$

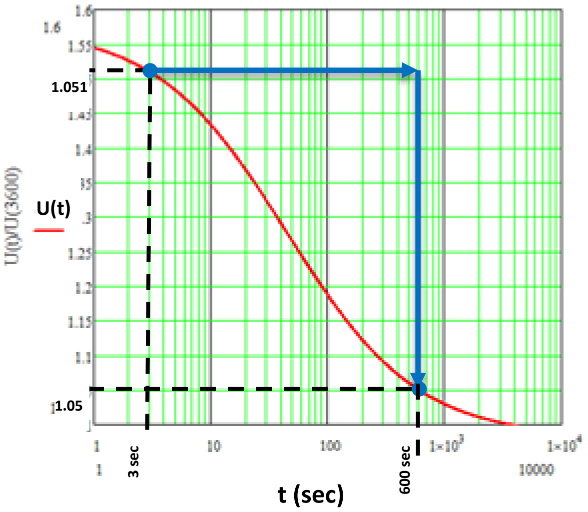


Figure 2 – Durst Curve [2]

With the Eurocode, U_{max} can be obtained

$$U_{\max} = \overline{U}_{10\min} \sqrt{1 + 7 I_u(z)} \qquad (3)$$

with $\overline{U}_{10\min}$ = mean value on 10 minutes of wind speed

$I_u(z)$ = turbulence intensity= 0.128

$U_{\max} = \overline{U}_{10\min}\, 1.38$

where the turbulence intensity $I_u(z)$ depends on the roughness of the ground.

With the Eurocode, U_{10min} is used to obtain the

Serviceability Limit State (SLS) for which the deformations are verified. The internal forces in SLS are multiplied by a safety factor of 1.5 for the resistance verification, named Ultimate Limit State, ULS (4).

$$\overline{U}_{10\min} \rightarrow \left.\begin{matrix}\text{SLS}\\ \text{deformation}\end{matrix}\right] x\ 1.50 \rightarrow \left[\begin{matrix}\text{ULS}\\ \text{resistance}\end{matrix}\right. \qquad (4)$$

3.3.2 During the construction phases

In the Eurocode, it is sufficient to change the Return Period, for example, TR= 10 years. The equation (1) is used to find mean wind speed $U_{10min,TR10years}$. The SLS internal forces are evaluated and multiplied by the safety factor, γ = 1.50, to verify the resistance.

In the AASHTO, the return period to consider is 20 years. The internal forces are after multiplied by a ponderation factor of 1.40 to verify the resistance. The approach is fundamentally different from the case of the structure in service (see 3.3.1.) and is similar to the Eurocode.

3.4 TR700years versus TR50years

If the reference wind speed is different, will the design wind forces be different?

The buffeting and resistance (ULS) are computed with the following data:

- Case 1 - AASHTO, $U_{TR700years}$ = 36.2 m/sec
  Resistance: ponderation factor = 1.00
- Case 2- Eurocode, $U_{TR50years}$ = 36.2 / 1.14 m/sec
  ULS: safety factor, γ = 1.50

All other data (turbulence intensities, turbulence length scales, coherence, power spectral density,…): same for both cases.

The internal forces are compared in the fig.3 and 4.

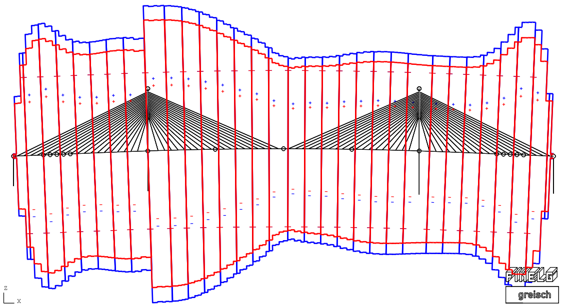


Figure 3 – N (normal force)
($TR_{700years}$ x 1.0) vs ($TR_{50years}$x 1.50)

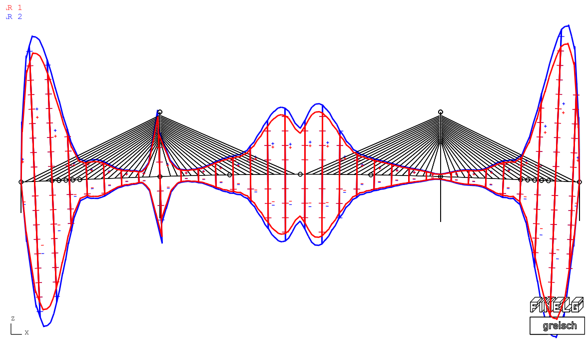


Figure 4 – MY (in-plane bending moment):
($TR_{700years}$ x 1.00) vs ($TR_{50years}$ x 1.50)

It can be observed that the internal forces are different:

- $N_{TR50years \times 1.5} = (N_{TR700years \times 1.0}) \times 1.14$
- $MY_{TR50years \times 1.5} = (MY_{TR700years \times 1.0}) \times 1.13$

The response is the combination of two parts (static ± dynamic). The difference is mainly due to turbulent component of the response, the dynamic part.

Internal wind forces are similar according both approaches but EUROCODE is slightly more safe or less economic. It is not so significant.

4 Power Spectral Density (PSD) – von Karman vs Kaimal

For the buffeting evaluation, the von Karman's PSD seems to be frequently used with no much discussion. But another one, the Kaimal's PSD is also frequently mentioned with the difficulty that several definitions are founded in the literature. The Eurocode EN 1991-1-4 proposes one definition. It would be interesting to compare the results obtained with both PSD.

$$Kaimal - EC1: \frac{n\,S_u(z,n)}{\sigma_u^2} = \frac{6.8\,f_L(z,n)}{(1+10.2\,f_L(z,n))^{5/3}}$$

$$with\ f_L(z,n) = \frac{n\,L_u(z)}{\overline{U}(z)} \tag{5}$$

$$von\ Karman: \quad \frac{n\,S_u(n,U)}{\sigma_u^2} = \frac{4\,L_u(z)/U(z)}{\left[1+70.7\,(n\,L_u(z)/U(z))^2\right]^{\frac{5}{6}}} \tag{6}$$

With : n, the frequency

z, the altitude

$S_u(n, U)$, the spectral density

σ_u, standard deviation of the wind speed

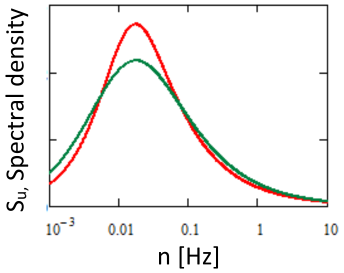


Figure 5 – PSD Kaimal (green), von Karman (red)

As in § 3.1.2., the data are identical for both cases except the PSD:

- case 1: von Karman, $UTR_{50years}$, $\gamma = 1.50$
- case 3: Kaimal, $U_{50years}$, $\gamma = 1.50$

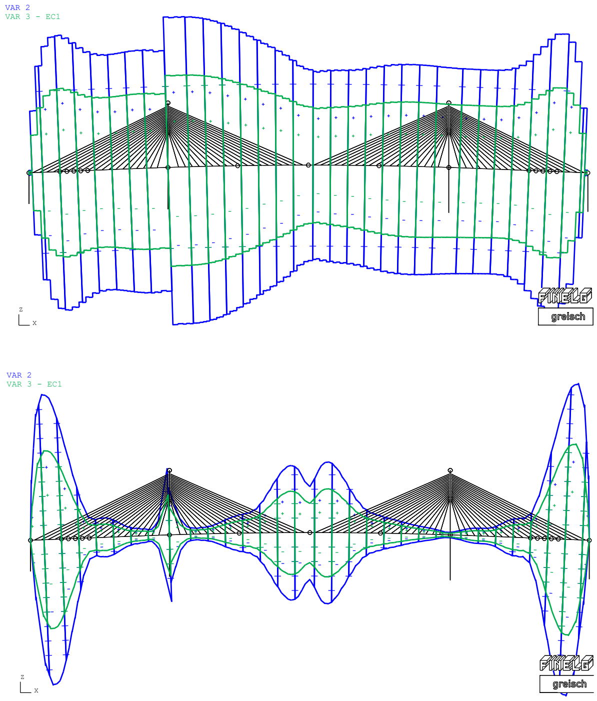


Figure 6 – N, My, comparison von Karman (case 1-blue) and Kaimal (case 3-green)

We see that von Karman induces internal forces larger than Kaimal (EC1).

The ratio between both cases is about equal to

- $N_{Kaimal} = (N_{von\ Karman}) / 1.50$
- $My_{Kaimal} = (My_{von\ Karman}) / 1.50$

5 Local data's

5.1 Turbulence Length scales and coherence functions

The length scales of gusts and the coherence functions are important for the wind loading.

The wind signal is composed of a constant wind speed (→ static loading) and a variable part along the bridge (→ no uniform spatial distribution and no constant versus the time). The variable component depends on the gusts shape defined by the turbulence length scales in the tree directions of the wind. They give the 3D dimensions of the gusts. More the turbulence length scales are great, more the spatial distribution will be “uniform”. The unity of the turbulence length scales is the meter [m]. Nine turbulence length scales can be given: in the tree local axes of the wind (u, v, w) and three local axes of the bridge (x, y, z): $L_{x,y,z}^{u,v,w}$.

The PSD depend on these parameters (eq. 5-6).

The effect of the coherence coefficients, C_{ij}, is given by:

$$S_{u1,u2}^{2}(n) = S_{u1}(n).S_{u2}(n).e^{\left(-\sqrt{(C_y^u \frac{y1-y2}{z1+z2})^2+(C_z^u \frac{z1-z2}{z1+z2})^2}\right).\frac{n}{U_{mean}}}$$

$$S_{ui} = \textit{power spectral density of wind force} \qquad (7)$$

Eq. (8) gives the total response of the buffeting.

$$\begin{aligned}
&\text{Buffeting response} = \text{static } (U_{\text{mean}}) \pm g\sqrt{\text{background + dynamic}} \\
&\quad g\text{, the gust factor} = 3.0 \text{ to } 4.0 \\
&\quad \text{background} = \text{fct(spatial distribution, coherence, } C_{u,v,w}^{y,z}) \\
&\quad \text{dynamic} = \quad \text{fct(PSD, lenght scales, } L_{u,v,w}^{x,y,z})
\end{aligned} \qquad (8)$$

The turbulence length scales depend strongly on the latitude of the bridge region.

> *Latitude is the geographic coordinate that specifies the north-south position of a point on the surface of the Earth. Latitude is given as an angle that ranges from −90° at the south pole to 90° at the north pole, with 0° at the Equator (Wikipedia).*

This is commonly accepted by wind experts that the dimensions of the gusts (turbulence length scales) depend on the Coriolis force.

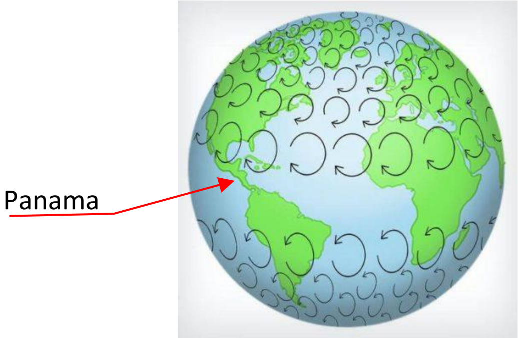


Figure 7 – effect of the Coriolis force on the dimensions of wind vortices [6]

The Coriolis force is produced by the additional acceleration due to the Earth's rotation and exerted on all moving bodies on the Earth's surface. It determines the general direction of winds and ocean currents, deflecting them to the right in the Northern Hemisphere, to the left in the Southern Hemisphere. It is null along the equator.

For our developments, the bridge is located near Panama City. Its latitude is 8,4°. 20° has been adopted for safety. On fig.7, we see that the dimensions of the gusts are larger in central America than in Europa and in USA. It would explain that in AASHTO and in Eurocode [1], the classical value of $L_x^u(z)$ is around 200-300 m.

$$\begin{aligned}
EC1: \quad & L_u^x(z) = 300\left(\frac{z}{200}\right)^{\alpha} \\
& \textit{with } \alpha = 0.67 + 0.05\ln(0.01) \\
& z = 82\,m \\
& \rightarrow L_u^x(82) = 203\,m
\end{aligned} \qquad (9)$$

For the other regions, ESDU 85020 [5] gives the procedure to calculate the turbulence length scales.

The steps of the calculation are numerous and would complicate the understanding of the text. On the other hand, it is interesting to give the most significant parameters considered to evaluate this turbulence length scale:

- The latitude of Panama, $\phi = 20°$,
- The rotation of the earth, $\Omega = 72.9\ 10^{-6}$ rad/sec,
- The Coriolis parameter, $f = 2\ \Omega \sin(\phi)$,
- The turbulence intensity at z = 82m, the level of the deck above sea level,
- The average wind speed at 10 m, for a rough terrain with zo = 0.03 m,
- The density of the air, ρ.

As a reminder, a turbulence length scale is associated with a PSD via the autocorrelation function, ρ_{uu}, through the inverse Fourier transform, by the relation (10).

$$L_u^x = U(z)\int_0^{\infty} \rho_{uu}\, d\tau \qquad (10)$$

For the bridge studied, associated with von Karman's spectral density, L_u^x value is

$$L_u^x = 501 \text{ m} \qquad (11)$$

By way of comparison, according to the ESDU procedure, the turbulence length scale for Ghent, would have the value,

$$L_{u,\text{Ghent}}^x = 286 \text{ m} \qquad (12)$$

To obtain this value, only the latitude, ϕ , has been changed (Ghent, ϕ =51°).

L^{x}_{u},Ghent (eq.12) is the order of magnitude proposed by the Eurocode. What must therefore be remembered is that a calculation standard is written according to a certain number of "local" parameters. The Eurocode concerns essentially structures in Europe and AASHTO, structures in the USA.

For this new comparison, the data that change are the "local" data: the turbulence length scales and the coherence coefficients.

- case 2: local data (Panama)
  L^{x}_{u} = 501 m, L^{y}_{u} = 182 m, L^{z}_{u} = 113 m,
  L^{x}_{w} = 55 m, L^{y}_{w} = 30 m,
  C^{y}_{u} = 8.8, C^{y}_{v} = 5.3, C^{y}_{w} = 6.4,
  C^{z}_{u} = 7.6, C^{z}_{v}= 5.0, C^{z}_{w} = 5.2,
  C^{x}_{u} = 3.0.

- case 4: data of North America
  L^{x}_{u} = 258 m, L^{y}_{u} = 86 m, L^{z}_{u} = 84 m
  L^{x}_{w} = 129 m, L^{y}_{w} = 16 m,
  C^{y}_{u} = 10, C^{y}_{v}= 10, C^{y}_{w} = 10,
  C^{z}_{u} = 10, C^{z}_{v} = 10, C^{z}_{w} = 10
  C^{x}_{u} = 10

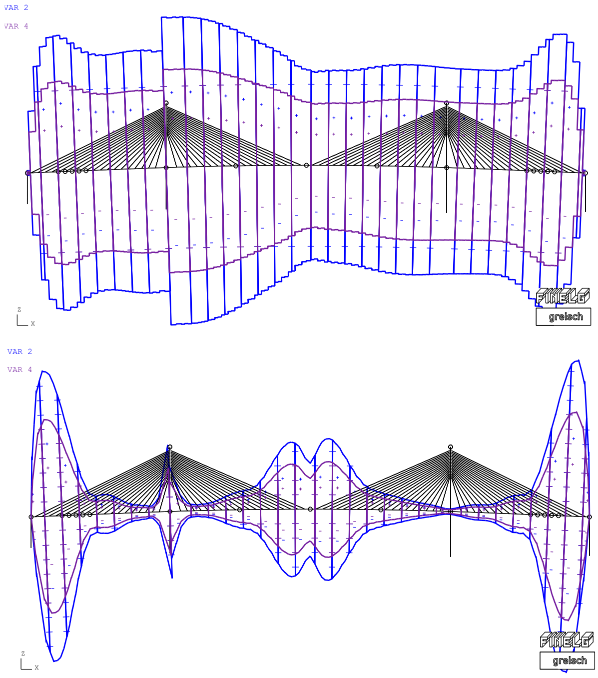


Figure 8 - N, My, local data (case 2-blue) vs data northern hemisphere (USA) (case 4-purple)

The ratio between both cases is about equal to

- $N_{local} = N_{USA}$ x 1.55
- $My_{local} = My_{USA}$ x 1.50

6 Summary of examined cases and conclusions

The figure 9 gives the opportunity to compare the effects of the four cases

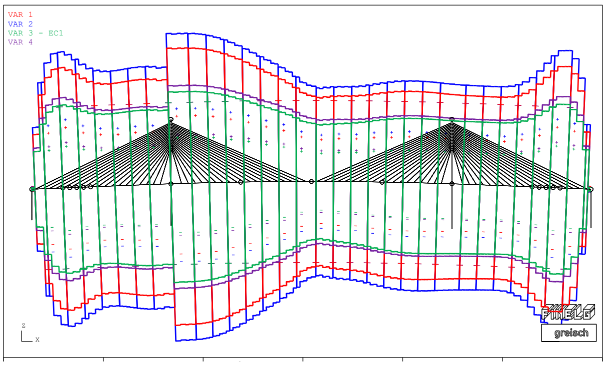
- Case 1 (red):
  Return Period = 700 years and safety factor, $\gamma_{\text{wind loads}}$ = 1.00
  von Karman PSD
  local turbulence length scales

- Case 2 (blue):
  Return Period = 50 years and $\gamma_{\text{wind loads}}$ = 1.50
  von Karman PSD
  local turbulence length scales

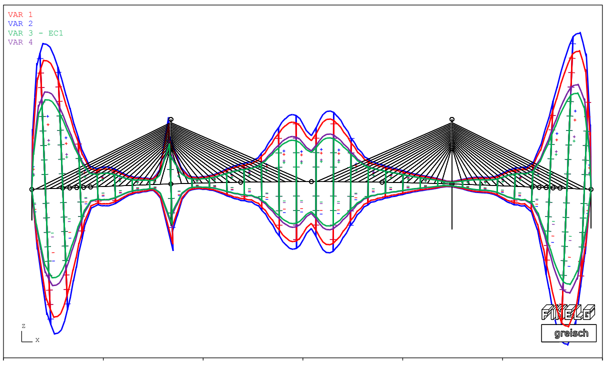
- Case 3 (green):
  Return Period = 50 years and $\gamma_{\text{wind loads}}$ = 1.50
  Kaimal PSD
  local turbulence length scales

- Cases 4 (purple):
  Return Period = 50 years and $\gamma_{\text{wind loads}}$ = 1.50
  von Karman PSD
  USA turbulence length scales and coherence coefficients

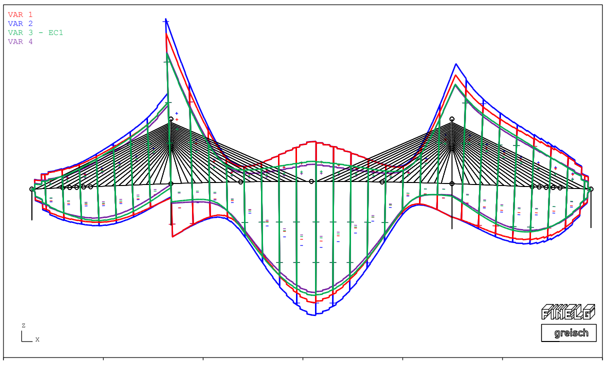
Case 2 > Case 1 >> Case 3 ≅ Case 4



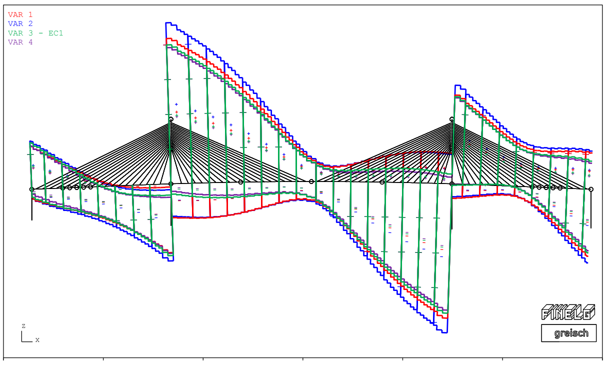
N – Normal forces



MY – in-plane bending moments



MZ - Out-of-plane bending moments



VY – out-of-plane shear forces

Figure 9 – Comparison of the four cases

It can be seen that:

- For the same structure (bridge)
- For a security assessment
- With three different hypotheses for the definition of wind characteristics

the value of the internal forces obtained is significantly different.

The standards specify that, for structures with a span larger than 200 m, a height of more than 150-200 m, the structure design office must contact experts.

But this approach is not enough. It is essential to establish a dialogue between the engineers of the design office and the experts in wind engineering. The design office is the expert for the behaviour of the structure, while the wind tunnel is an expert in wind data.

For a constructive dialogue, it would be really interesting to develop a document, a memo accessible to all, that would include and/or discuss the essential wind data and their consequences for the verification of a large structure under the effect of the wind:

- According to AASHTO or Eurocodes
- Data to adapt according to the location on earth globe
- Assumptions of the Wind Energy Modelling (PSD)
- The value of the return period, TR_{year}, and the safety factor associated
- …

IABSE would be well placed to lead the drafting of such documents, by setting up a working group bringing together wind engineering experts and engineers from design offices.

7 Acknowledgements

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8 References

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