Influence of bridge deck shape on extreme buffeting forces

Olivier Flamand [a], Vincent Denoël [b]

[a]CSTB, Nantes, France, olivier.flamand@cstb.fr
[b]University of Liège, Department of Architecture, Geology, Environment and Construction, Belgium, v.denoel@ulg.ac.be

1 INTRODUCTION

The design of a bridge deck with respect to wind action usually relies on a simple principle: as the average and standard deviation of aerodynamic coefficients are responsible for the buffeting excitation, minimizing them is supposed to be beneficial for extreme wind loads. Traditional bridge deck shapes are optimized in this view.

Seminal developments related to the establishment of peak factors for the estimation of the extreme loads are generally attributed to Cartwright and Higgins (1956). They have been widely applied, but fail to offer an accurate model in some circumstances as they are developed within the framework of Gaussian processes. Some less restrictive formulations are discussed and compared by Floris and Iseppi (1998). The non-Gaussianity of the wind loading is indeed an important issue as it affects the extreme wind forces, i.e. those that precisely have to be taken into account for the structural design. Such discussions indicate that a skewed random process might evince, even for a skewness coefficient as small as $\gamma_3 = 0.5$, peak factors that are 20% to 30% higher than those obtained with Gaussian developments (e.g. based on a model proposed in (Gurley et al., 1997)).

With that in mind, and being restricted to buffeting analysis, this paper proposes to supplement the traditional considerations about deck shape optimization with a discussion about the skewness of aerodynamic loading.

We consider a nonlinear wind loading model in which the skewness results, in part, from the nonlinearity of aerodynamic coefficients. Actually, in a quasi-steady context, these coefficients are measured for various angles of attack on the bridge deck. This typically results in a nonlinear coefficient .vs. incidence relation, which in turn is partly responsible for the non Gaussian distribution of the aerodynamic loading.

As a final objective, we endeavor at providing an estimation of the skewness of the aerodynamic loading that could be typically expected for a given bridge deck typology. In doing so, we believe the general trends that are observed in this study will help in assessing the effect of the choice of a bridge deck typology on the extreme wind force. This objective is reached in a two-step procedure. First a database analysis of several bridge decks is performed in order to provide, for three families of deck typology –box, girder, streamlined- ranges of variation of drag and lift coefficients. Then, based on a quasi-steady nonlinear aerodynamic model, these ranges are translated into skewness coefficient of aerodynamic forces.

2 NONLINEAR QUASI-STEADY WIND MODEL

For low wind velocities and limited structural motion, quasi-steady aerodynamic forces (per unit length) acting on a bridge deck are commonly expressed as

$$F = \frac{1}{2}\,\rho C B V^2 \tag{1}$$

where ρ is the air density, B is the deck width and V is the apparent wind velocity (Simiu and Scanlan, 1996). Symbol C stands for an aerodynamic coefficient, typically C_D or C_L, drag or lift, in bridge applications. (A similar expression with different units exists for the overturning moment.) These coefficients are measured through wind-tunnel experiments performed on rigid section models placed in a laminar or turbulent flow, and are here expressed in the wind reference system as in Fig. 1. Measurements are repeated for a series of wind incidences α covering the range of incidences expected on the construction area, and for a sufficiently large Reynolds number. The resulting function $C(\alpha)$ is typically nonlinear, as seen in the next sections, and might be fitted by a polynomial of any degree N (Denoël, 2009) as

$$C(\alpha) = \sum_{i=0}^{N} \frac{c_i}{i!} \alpha^i. \tag{2}$$

The function is usually linearized, but the main scope of this paper is to study the influence of its nonlinearity (as well as that of other nonlinear terms) on the skewness of aerodynamic forces.

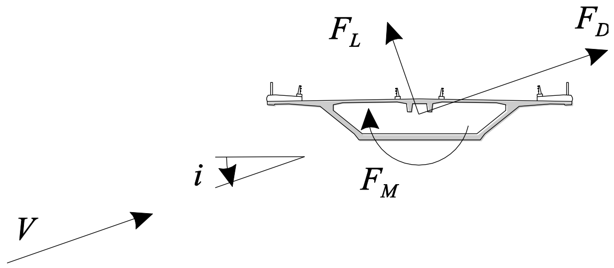

Figure 1: Sign conventions for quasi-steady wind forces.

There exists a time varying formulation of (1) where the apparent velocity and wind incidence change with time, as a result of the turbulence created in the atmospheric boundary layer (Holmes, 2007)

$$F(t) = \frac{1}{2} \rho \, C[\alpha(t)] B V^2(t). \tag{3}$$

In 2-D applications, the wind velocity is decomposed into a mean wind velocity U and the corresponding direction, plus two zero-mean turbulence components $u(t)$ and $v(t)$, Solari and Piccardo (2001). The apparent velocity $V(t)$ and wind incidence $\alpha(t)$ are then expressed as

$$V^2(t) = \left(U + u(t)\right)^2 + w^2(t) \quad \text{and} \quad \alpha(t) = \tan^{-1} \frac{v(t)}{U + u(t)}. \tag{4}$$

At this stage, advanced aerodynamic loading models build up this formulation with admittances or relative structural velocity (Scanlan and Jones, 1999). These refinements are simply disregarded in this work, in which the intrinsic nonlinearity of the quasi-steady loading (3) is investigated.

Indeed, although a number of papers deal with the nonlinearity resulting from the squared velocity in (4a), (Soize, 1978, Lutes, 1986), in this work we consider a further refined 2-D aerodynamic model including not only that quadratic nonlinearity but also that from the angle of attack (4b) and the aerodynamic coefficient $C(\alpha)$.

3 DECK TYPOLOGY AND AERODYNAMIC COEFFICIENT

According to (3), aerodynamic forces on a bridge deck depend on its shape, through aerodynamic coefficients. Surprisingly, there have been few attempts at connecting deck typologies (streamlined, box or twin) with aerodynamic coefficients.

In this field, we may underline the works of (Bienkiewicz, 1987; Kubo et al., 2002; Pindado et al., 2005; Lin et al., 2005) who mainly aim to study simple geometrical sections such as trapezoid, rectangular, triangular, and to derive for them generic aerodynamic coefficient, eventually for various flow regimes. Other contributions focus on details such as the presence of fairings (Nagao et al., 1993), or even the influence of turbulence on mean aerodynamic forces (Walshe, 1981) or flutter velocities (Diana et al., 1993). Another noticeable contribution consists in mapping Scanlan coefficients to realistic classes of deck sections (Mannini, 2006). A first part of this paper consists in complementing these kinds of studies with realistic bridge deck sections.

To do so, measurement reports are compared for 18 realistic projects of bridge deck tested in the NSA wind-tunnel of the CSTB in Nantes. An interesting feature of this study is that all bridge decks are tested in the same wind-tunnel, with the same measurement team, and the same acquisition procedure. These bridge decks a classified into three deck typologies, according to their shape, see Fig. 2, namely streamlined, box, twin girders.

A limited amount of classes was deliberately selected, as a consequence of the limited total number of available deck shapes; the classification of a bridge deck in one or another class of typology was made rather heuristically from consideration of its global shape. Some shapes indicators could be used to determine automatically the appurtenance of a given deck to a certain class, or eventually when it is intermediate between various classes (for instance, here, deck 15 is classified in twin girder decks although it could be seen as a streamlined girder too).

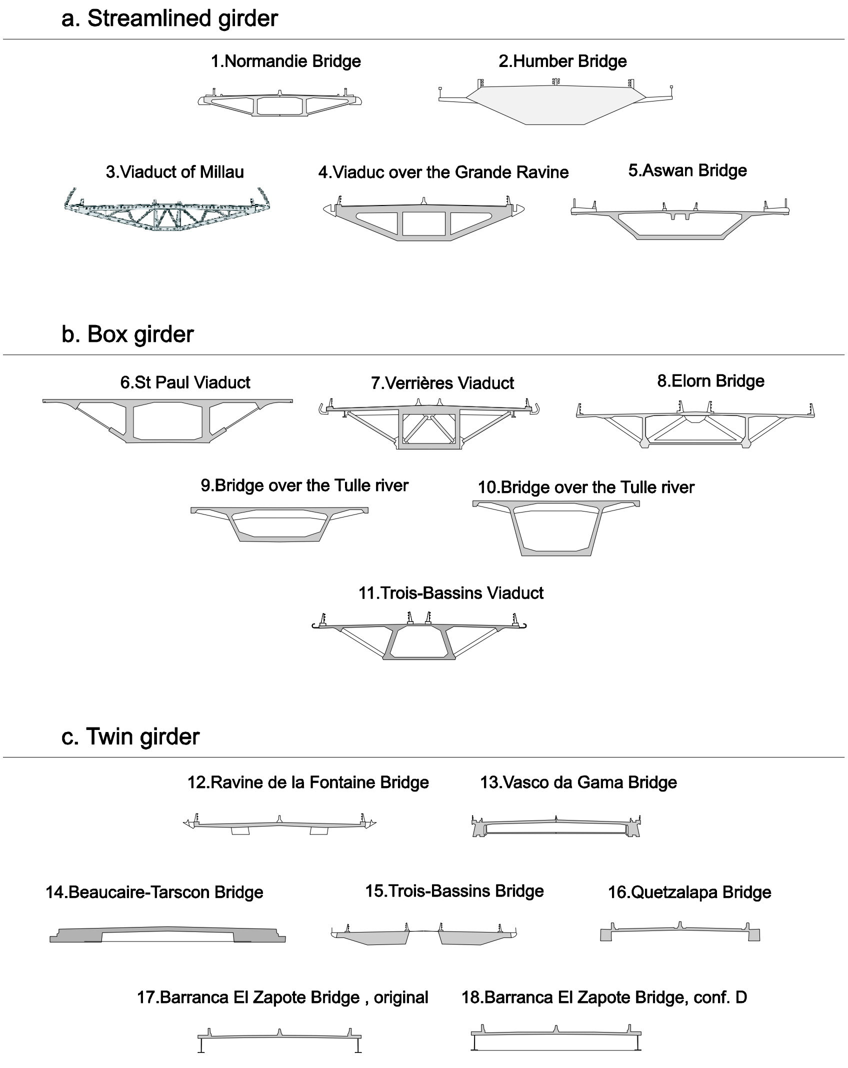

Figure 2: Classification of bridge deck sections.

Aerodynamic coefficients measured for those bridge decks are then collected typology by typology, see Fig. 3. This discriminating representation indicates some global trends for each deck typology: streamlined decks naturally disclose a low drag coefficient with a low sensitivity to wind incidence; box girders are characterized by a larger drag whereas twin deck evince a significant quadratic dependency upon the wind incidence. Yet the pattern of lift coefficients shows to be typical for each typology: streamlined decks are almost linear with respect to the wind incidence, while box girders exhibit a negative curvature, and twin decks show an S-pattern.

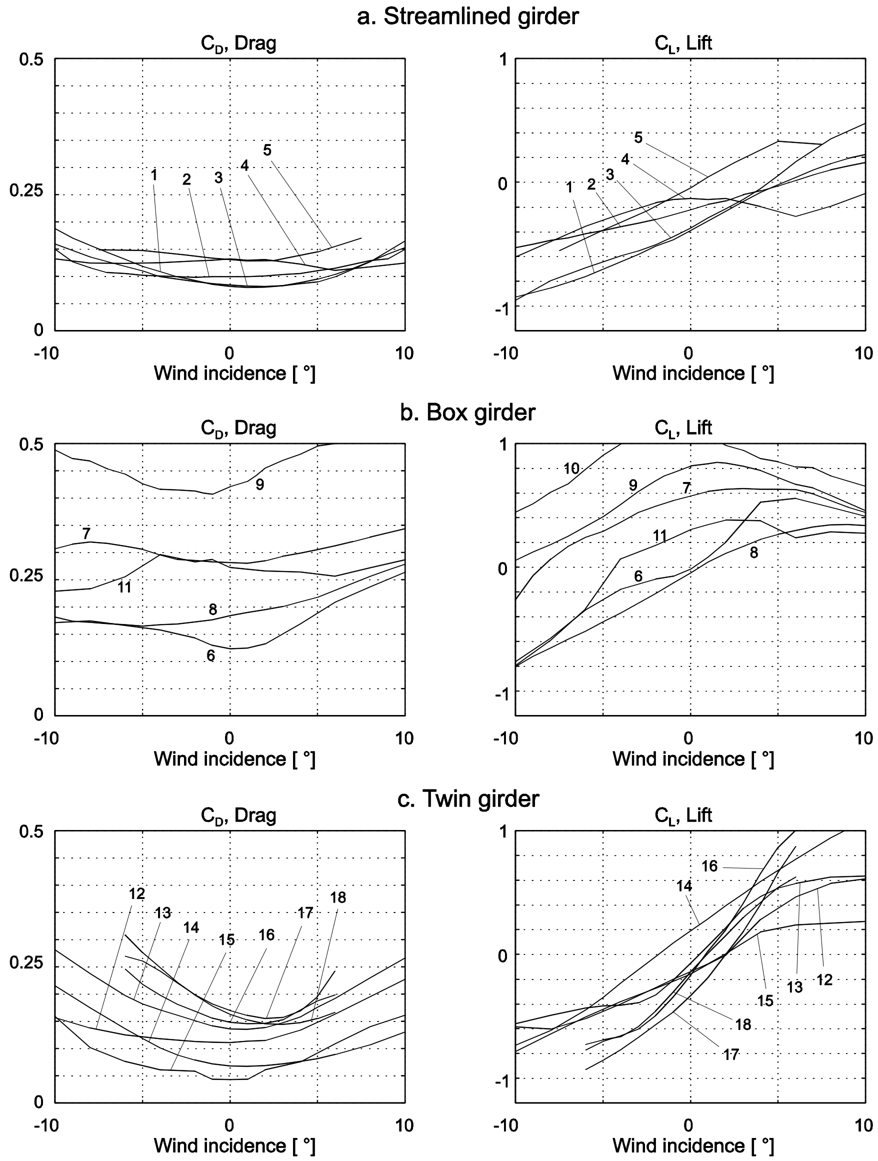

Figure 3: Aerodynamic coefficients (for each typology).

These visual trends are objectified by fitting a quadratic polynomial on the measured aerodynamic coefficient, as in (2), with the procedure described in (Denoel, 2009). This procedure consists in fitting a polynomial to the measured data, in the stochastic polynomialization sense. The ranges of variation of coefficients c_0, c_1 and c_2 are then represented in a pattern space, Fig. 4. For the subset of decks corresponding to each typology, boxes indicate the average plus/minus one standard deviation of drag (left) and lift (right) coefficients. The same trends as before are globally observed. For instance, coefficient c_2 is small for streamlined decks, which indicates a somewhat linear dependency upon wind incidence.

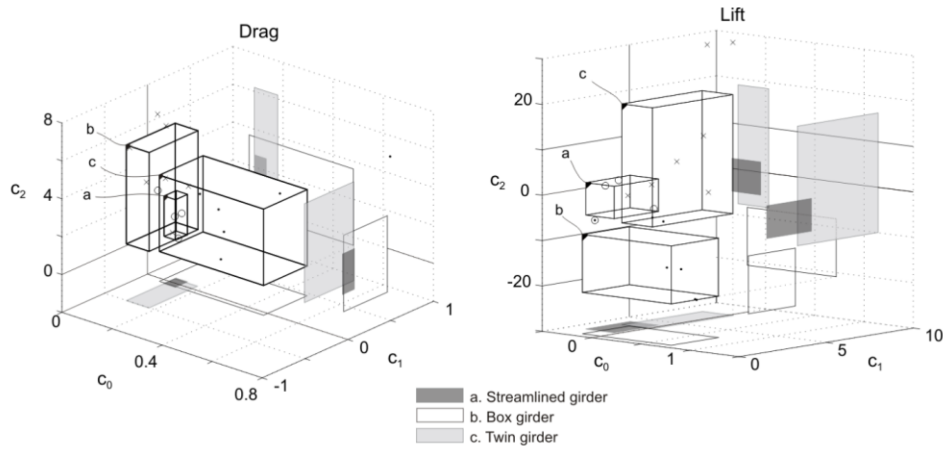

Figure 4: Subspace representing the shape of aerodynamic coefficients for various deck typologies.

With these ranges, we are now in a position to determine, for each deck typology, the characteristics of the aerodynamic loading resulting from a quasi-steady model as (3). In particular, we mainly focus next on the skewness of the loading, a commonly disregarded issue.

4 STATISTICS OF AERODYNAMIC FORCES

Although there are evidences that the atmospheric turbulence is a non Gaussian phenomenon (Jones, 2007), the turbulence components $u(t)$ and $v(t)$, as introduced in (4), are usually modeled as Gaussian processes with a joint probability density function (pdf) given as

$$p_{uv}(u,v) = \frac{1}{2\pi I_u I_v U^2\sqrt{1-\rho^2}} e^{\frac{-1}{2(1-\rho^2)U^2}\left(\frac{u^2}{I_u^2}-\frac{2\rho uv}{I_u I_v}+\frac{v^2}{I_v^2}\right)}. \tag{5}$$

where I_u and I_v represent the turbulence intensities and ρ their correlation coefficient. Because the aerodynamic forces resulting from the quasi-steady loading are expressed as a function of the turbulence components, through (3), the pdf of the aerodynamic force could, in principle, be expressed explicitly (Papoulis, 1965). This would however result in a heavy mathematical expression. Instead, we consider next a simpler expression obtained by considering the smallness of the turbulence intensities (Denoël, 2009), i.e. $I_u \ll 1$ and $I_v \ll 1$.

4.1 *Mean aerodynamic force*

With this assumption the mean aerodynamic force is given as

$$\mu_f = \frac{1}{2}\rho B U^2 (c_0 + c_1 \rho I_u I_v + \frac{c_2}{2} I_v^2) \,. \tag{6}$$

In view of ranges of variation of pattern numbers c_0, c_1 and c_2, and with typical orders of magnitude of wind intensities, this relation usually cuts down to

$$\mu_f = \frac{1}{2}\rho B U^2 c_0, \tag{7}$$

except for bridges with a small mean aerodynamic coefficient c_0 (for example lift of streamlined decks), or a very large c_2 (i.e. large curvature).
This reasoning is in agreement with the usual objective consisting in minimizing the mean aerodynamic coefficient c_0, in order to minimize the mean aerodynamic force. Streamlined decks are naturally optimum in this view. Notice however that $c_0 = 0$, in the limit case, does not result in a zero-mean force; in that case the mean force is given by (6).

4.2 *Variance of the aerodynamic force*

Under the same assumption regarding the smallness of turbulence intensities, the mean square force (the second statistical moment) is given as

$$m_{2,f} = \left(\frac{1}{2}\rho B U^2\right)^2 \left(c_0^2 + c_1^2 I_w^2 + \frac{3}{4} c_2^2 I_w^4 + c_0 c_2 I_w^2 + 6 c_0 c_1 I_u I_w + 3 c_1 c_2 I_u I_w^3 \rho\right). \tag{8}$$

It features an ellipsoidal shape in the pattern coefficient space, as expressed by common loading models (Holmes, 2007). As a consequence, the variability of the aerodynamic loading may result from (i) the mean aerodynamic coefficient, (ii) a significant transverse turbulence combined with a significant first or second derivative of the aerodynamic coefficient with respect to the angle of attack. The orders of magnitude of c_2 and I_w reveal that the curvature of aerodynamic coefficient cannot be responsible for a significant extra loading. This justifies the linearization of usual aerodynamic models, for the estimation of the mean and standard deviation of aerodynamic forces.

With the typical ranges of variation for pattern numbers c_0 and c_1, as given in Fig. 4, one may observe that streamlined decks generate the smallest variability in the drag force. Box girders and twin deck result in significant variances of aerodynamic forces, for the two different reasons given above, namely, large c_0 for the one, and large c_1 (relatively) for the other.

Furthermore, box girders show a response in lift slightly superior to streamlined decks, whereas twin deck generate large aerodynamic forces as a consequence of a large sensitivity of the lift coefficient with respect to the angle of attack.

4.3 *Skewness of the aerodynamic force*

The same developments can be derived for the next order, related to the symmetry of the probability distribution of aerodynamic forces. With the same assumption again, the third moment writes

$$\begin{aligned} m_{3,f} = \left(\frac{1}{2}\rho B U^2\right)^2 \Big(& c_0^3 + \frac{9}{2} c_1^2 c_2 I_w^4 + \frac{15}{8} I_w^6 c_2^3 + 9 c_1^3 \mathrm{Iu} I_w^3 \rho + \frac{45}{4} c_1 c_2^2 \mathrm{Iu} I_w^5 \rho + \frac{3}{2} c_0^2 c_2 I_w^2 \\ & + 15 c_0^2 c_1 \mathrm{IuIw} \rho + 3 c_0 c_1^2 I_w^2 + \frac{9}{4} I_w^4 c_0 c_2^2 + 27 c_0 c_1 c_2 \mathrm{Iu} I_w^3 \rho\Big) \end{aligned} \tag{9}$$

The skewness coefficient is a dimensionless version of the third central moment, obtained as

$$\gamma_3 = \left(m_{3,f} - 3 m_{1,f} m_{2,f} + 2 m_{1,f}^3\right) / \left(m_{2,f} - m_{1,f}^2\right)^{3/2} \tag{10}$$

It is usually preferred thanks to its simple physical intuition.

Figure 5 represents, in the pattern number space, the skewness coefficient as obtained with (10), and for $I_u = I_v = 10\%$ and $\rho = 0$. Rectangles indicate the typical ranges of variation introduced in Fig. 4 for each deck typology. Four slices corresponding to various values of c_2 are cut out of the pattern number space (c_0, c_1, c_2); rectangles associated to each typology do not appear in each subplot. As a matter of fact, an optimal design should therefore limit the skewness of aerodynamic forces, in order to limit extreme values of the forces generated on the deck. For this reason, we propose to represent the mapping of the skewness coefficient along the pattern number space, and more specifically to point out areas where it exceeds $\gamma_3 = 0.5$, i.e. areas from which an optimum design should ideally be kept clear from (following the guidelines outlined in Section 1).

Actually, an optimum design requires the probability density function of the loading to be skewed in a direction opposite to the mean values. As the mean dimensionless force is approximately equal to c_0, the skewness coefficient should be less than $\gamma_3 = 0.5$ for $c_0 > 0$ and larger than $\gamma_3 = -0.5$ for $c_0 < 0$. In the context of drag forces, this latter case is however not met; the relevance of the design might therefore be assessed by the unique condition $\gamma_3 < 0.5$.

Concerning drag forces, streamlined decks appear to be insensitive to the non-Gaussianity (with the limitation that the ranges of variations of pattern numbers are indicative rather than conservative ranges). On the contrary, twin decks seem to be prone to a high skewness of wind forces, especially because their drag coefficients are significantly curved. Figure 5 indicate skewness coefficients larger than 1.

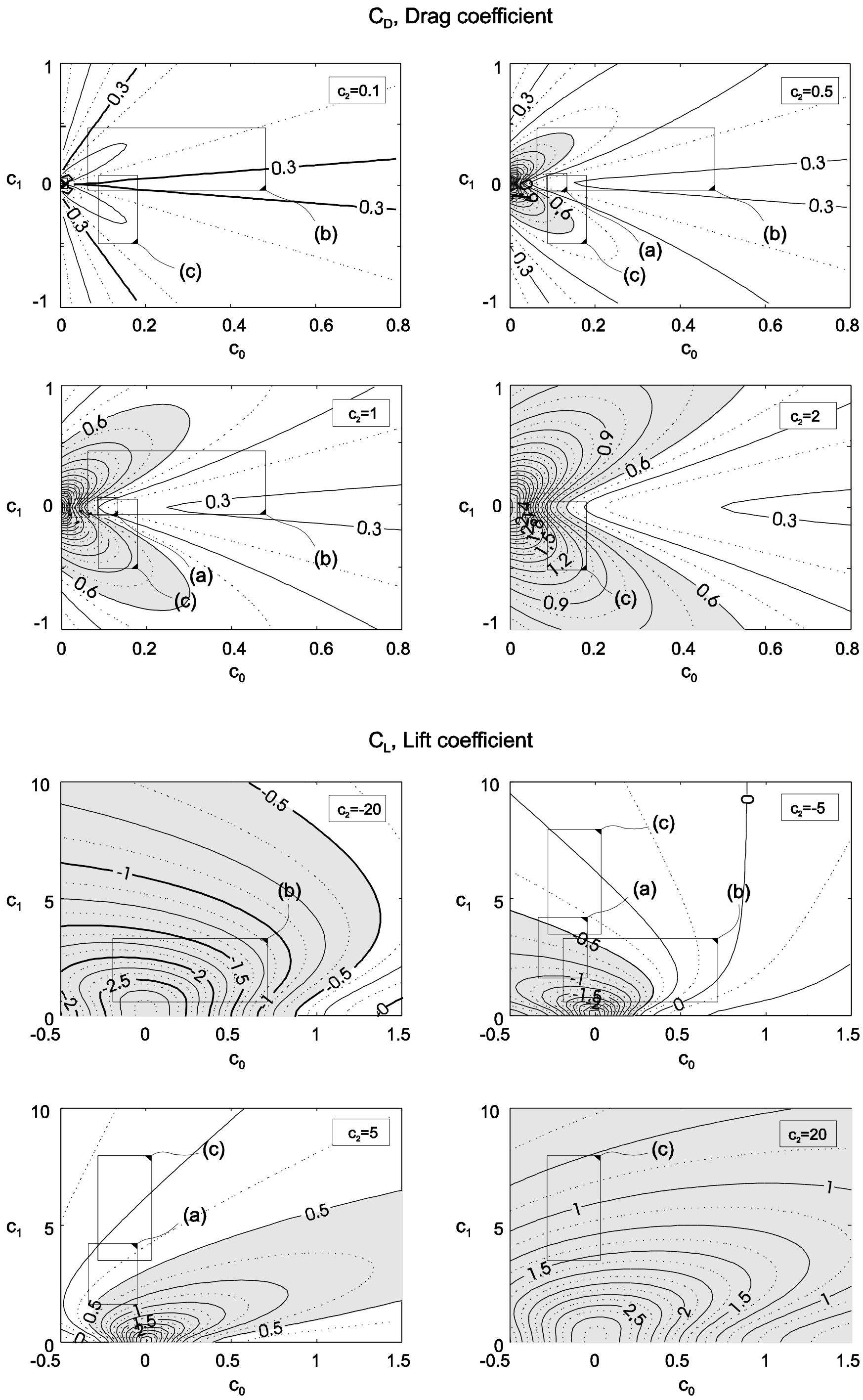

Figure 5: Skewness coefficient of drag and lift forces. Rectangles indicate ranges of variation of the pattern numbers c_0, c_1 and c_2 for each deck typology: (a) streamlined girder, (b) box girder and (c) twin girder.

Skewness coefficients of lift forces are also represented in Fig. 5. Level curves are actually identical to those represented for drag forces; just the extents of the plots related to each force are dissimilar in view of the different ranges covered by drag and lift pattern numbers respectively.

Subplots of Fig. 5 reveal that the sign of the skewness coefficient of the lift force is that of pattern number c_2. As a moderate negative skewness, combined with a significantly positive mean force, is an interesting way to reduce extreme forces, some box girder configurations (with large c_0) might be seen as the only way to reduce extreme forces, compared to what should be obtained with a Gaussian model. Streamlined decks are characterized by a small $|c_0|$, which indicates that any significant skewness is harmful, no matter its sign. The pattern numbers of this typology should therefore be examined cautiously, as they might lead to problematic design in case of too low c_0 and/or c_1.

5 CONCLUSIONS

A quasi-steady nonlinear wind loading model is considered in this paper in order to assess the influence of the nonlinearity of aerodynamic coefficiens (with respect to the angle of attack) on the skewness of the aerodynamic loading.

In a first part, pattern numbers (intercept, slope and curvature) of aerodynamic coefficient of some deck typologies are given. They are obtained from a database analysis of realistic deck sections tested in the same wind-tunnel and under the same testing procedure.

Besides, a mapping of the skewness coefficient of the aerodynamic loading was represented in the pattern number space. This representation, along with the typical ranges of interest pertaining to each deck typology, is an interesting tool to predict the susceptibility of a new project to exhibit extreme values larger that a Gaussian process. The most interesting trends are that (i) streamlined decks may be modeled accurately with a Gaussian model, for all that the deck is not marginal with respect to the average aerodynamic coefficients; (ii) for box girder decks, a large scatterness of pattern coefficients -owing to the significant variability of deck height/width ratios- is observable. In view of the design objectives considered in this paper, i.e. the limitation of the skewness of the loading, box girder decks seem to be effective: the drag force is generally non-skewed, and the lift force is, in most cases, skewed in a direction opposite to that of the mean force, which naturally reduces extreme values; (iii) twin girder decks are definitely those that are the most susceptible to produce a significantly skewed loading, for both drag and lift forces.

6 REFERENCES

Bienkiewicz, B. (1987). "Wind-tunnel study of effects of geometry modification on aerodynamics of a cable-stayed bridge deck." Journal Of Wind Engineering And Industrial Aerodynamics 26(3): 325-339.

Cartwright D.E., Longuet-Higgins M.S., "The Statistical Distribution Of The Maxima Of A Random Function," Proceedings Of The Royal Society Of London Series A-Mathematical And Physical Sciences, vol. 237, pp. 212-232, 1956.

Denoël, V. (2009). "Polynomial approximation of aerodynamic coefficients based on the statistical description of the wind incidence." Probabilistic Engineering Mechanics 24(2): 179-189.

Denoël, V., Flamand, O., 2011. Influence of bridge deck typology on extreme buffeting forces. Journal of Wind Engineering and Industrial Aerodynamics, in Press.

Diana, G., S. Bruni, et al. (1993). "Turbulence effect on flutter velocity in long-span suspended bridges." Journal Of Wind Engineering And Industrial Aerodynamics 48(2-3): 329-342.

Floris C.,D’Iseppi L., "The Peak Factor for Gust Loading: A Review and Some New Proposals," Meccanica, vol. 33, pp. 319-330, 1998.

Gurley, K.R., Tognarelli, M.A., Kareem A., "Analysis and simulation tools for wind engineering," Probabilistic Engineering Mechanics, vol. 12, pp. 9-31, 1997.

Holmes, J. D. (2007). Wind Loading on Structures. London, SponPress.

Jones, J. G. (2007). "Measured statistics of multicomponent gust patterns in atmospheric turbulence." Journal Of Aircraft 44: 1559-1567.

Kubo, Y., K. Kimura, et al. (2002). "Aerodynamic performance of improved shallow pi shape bridge deck." Journal Of Wind Engineering And Industrial Aerodynamics 90(12-15): 2113-2125.

Lin, Y.-Y., C.-M. Cheng, et al. (2005). "Effects of deck shape and oncoming turbulence on bridge aerodynamics." Tamkang Journal of Science and Engineering 8(1): pp. 43-56.

Lutes, L. D. and S. L. J. Hu (1986). "Nonnormal Stochastic Response Of Linear-Systems." Journal Of Engineering Mechanics-Asce 112(2): 127-141.

Mannini, C. (2006). Flutter vulnerability assessment of flexible bridges. Department of Civil Engineering. Braunschweig, Technical University Carolo-Wilhelmina: 207. PhD Thesis.
Nagao, F., H. Utsunomiya, et al. (1993). "Aerodynamic efficiency of triangular fairing on box-girder bridge." Journal Of Wind Engineering And Industrial Aerodynamics 49(1-3): 565-574.
Papoulis, A. (1965). Probability, Random Variables, and Stochastic Processes. New York, McGraw Hill.
Pindado, S., J. Meseguer, et al. (2005). "The influence of the section shape of box-girder decks on the steady aerodynamic yawing moment of double cantilever bridges under construction." Journal Of Wind Engineering And Industrial Aerodynamics 93(7): 547-555.
Scanlan, R. H. and N. P. Jones (1999). "A form of aerodynamic admittance for use in bridge aeroelastic analysis." Journal Of Fluids And Structures 13(7-8): 1017-1027.
Simiu, E. and R. Scanlan (1996). Wind Effects On Structures, John Wiley and Sons.
Soize, C. (1978). "Gust loading factors with nonlinear pressure terms." Journal of the Structural Division ASCE 104: 991-1007.
Solari, G. and G. Piccardo (2001). "Probabilistic 3-D turbulence modeling for gust buffeting of structures." Probabilistic Engineering Mechanics 16(1): 73-86.
Walshe, D. E. (1981). Some effects of turbulence on fluctuating and time-average wind-forces on sectional models of box girder bridges. Bridge Aerodynamics. Institution of Civil Engineers, London, Thomas Teleford Limited.