Design Manual for Roads and Bridges

Highway Structures & Bridges
Design

CD 363
Design rules for aerodynamic effects on bridges

(formerly BD 49/01)

Revision 0

Summary
This document sets out the design requirements for bridges with respect to aerodynamic effects including provisions for wind-tunnel testing. It updates and supersedes BD 49/01.

Application by Overseeing Organisations
Any specific requirements for Overseeing Organisations alternative or supplementary to those given in this document are given in National Application Annexes to this document.

Feedback and Enquiries
Users of this document are encouraged to raise any enquiries and/or provide feedback on the content and usage of this document to the dedicated Highways England team. The email address for all enquiries and feedback is: Standards_Enquiries@highwaysengland.co.uk

This is a controlled document.

Contents

Release notes

Version	Date	Details of amendments
0	Jan 2020	CD 363 replaces BD 49/01. This full document has been re-written to make it compliant with the new Highways England drafting rules.

Foreword

Publishing information

This document is published by Highways England.

This document supersedes BD 49/01, which is withdrawn.

Contractual and legal considerations

This document forms part of the works specification. It does not purport to include all the necessary provisions of a contract. Users are responsible for applying all appropriate documents applicable to their contract.

Introduction

Background

The original version of these rules first appeared as the "Proposed British Design Rules" in 1981 ICE 1981 [Ref 2.I]. A modified version was included in the TRL Contractor Report 36 TRL CR36 [Ref 3.I], which also contained the associated partial safety factors and guidance on the use of the rules.

Major changes in 1993 version of BD 49

In the light of their use in bridge design from 1981, further consideration was deemed necessary with respect to a number of items. The more notable aspects embodied in the 1993 version of BD 49 were the rules which determined whether the designs of certain footbridges and steel plate-girder bridges needed to be based on wind tunnel testing.

Background information on these modifications is available in TRL CR256 [Ref 1.I].

Major changes in 2001 version of BD 49

Since the 1993 version of this standard, further wind tunnel tests have been carried out and other studies have been undertaken, which have led to further amendments to the rules. Background is provided in TRL RR530 [Ref 5.I]. The 2001 version of the rules incorporates the outcome of this work, including:

1) more reliable criteria for plate girder bridges, based on a comprehensive series of tests on wind tunnel models; and
2) a review of the rules in the light of experience leading to:
   a) improved considerations of edge details;
   b) amendments to all critical wind speeds;
   c) improved accuracy of vortex shedding amplitudes;
   d) more accurate criteria for aerodynamic susceptibility; and
   e) initial guidance on proximity effects.

Major changes in this version of BD 49 (now CD 363)

Many of the provisions of BD 49/01 have since been repeated in BS EN 1991-1-4 [Ref 3.N], NA to BS EN 1991-1-4 [Ref 7.N] and PD 6688-1-4 [Ref 2.N]. This version of BD 49 (now CD 363) only contains the provisions that have not been repeated in the above referenced documents and indicates where the repeated provisions are located.

Additional guidance

Guidance on the use of the design rules is available in TRL Contractor Report 36 TRL CR36 [Ref 3.I]. Actual bridge configurations being designed that may correlate with sections physically tested previously may benefit from use of the archive test data which are held in the library of the Institution of Civil Engineers ICE Box Girders [Ref 4.I].

Assumptions made in the preparation of this document

The assumptions made in GG 101 [Ref 6.N] apply to this document.

Symbols

Symbols

Symbol	Definition
b	Overall width of bridge deck
b'	Overall width of neighbouring bridge deck
b^*	Effective width of bridge deck
C_s	Coefficient to take account of the extent of wind speed range over which oscillation can occur
C_θ	Relative frequency of occurrence of winds within +/-10 degrees of normal to the longitudinal centre line of the bridge in strong winds
d_4	Depth of bridge deck
d'	Depth of neighbouring bridge deck
f	The natural frequency of a chosen mode, taken as n_b for a bending mode or n_t for a torsional mode
G	Clear gap between parallel bridges
G_1	Minimum gap between parallel bridges
G_2	Maximum gap between parallel bridges
L	Length of main span of bridge
m	Mass per unit length of bridge
n	Effective number of stress cycles per year
n_b	Natural frequency in bending
n_t	Natural frequency in torsion
P_b	Aerodynamic susceptibility parameter
p	Frequency of occurrence of wind speeds within +/- $2\frac{1}{2}$ % of the critical wind speed
R_e	Reynolds number
$v_{crit,i}$	Critical wind speed for vortex shedding
$v'_{crit,i}$	Critical wind speed for vortex shedding for the estimation of fatigue damage
v_f	Critical wind speed for classical flutter
v_g	Critical wind speed for galloping and stall flutter
$v_m(z)$	Mean wind speed at height, z
v_{Rf}	Reduced critical wind speed for classical flutter
v_{Rg}	Reduced critical wind speed for galloping and stall flutter
$y_{\max}$	Maximum amplitude of vibration of the deck
z	Height of bridge deck above ground level
$\overline{\alpha}$	Inclination of wind to horizontal due to local topography
γ_{fL}	Partial load factor

Symbols (continued)

Symbol	Definition
σ_r	Stress range
ϕ	Solidity ratio of parapet, or ratio of net total projected area presented to the wind to the total area encompassed by the outer boundaries of the deck for trusses

1. Scope

Aspects covered

1.1 The requirements within this document are for bridges with respect to aerodynamic effects, including provisions for wind-tunnel testing and this document shall supersede the previous version of this standard BD 49/01.

1.1.1 The document may be used to supplement BS EN 1993-2 [Ref 4.N] in respect of verification of aerodynamic effects on bridges by testing.

1.2 The requirements within this document shall be applied to all highway bridges and foot/cycle-track bridges.

1.3 This document's provisions shall only be used for bridges which comply with the constraints herein.

Implementation

1.4 This document shall be implemented forthwith on all schemes involving the design of highway bridges and foot/cycle-track bridges on the Overseeing Organisations' motorway and all-purpose trunk roads according to the implementation requirements of GG 101 [Ref 6.N].

Use of GG 101

1.5 The requirements contained in GG 101 [Ref 6.N] shall be followed in respect of activities covered by this document.

2. General requirements

2.1 The adequacy of the structure to withstand the dynamic effects of wind, together with other coincident loading, shall be verified in accordance with Eurocode 1 (BS EN 1991-1-4 [Ref 3.N]), as implemented by the DMRB (see PD 6688-1-4 [Ref 2.N]).

2.2 The design shall assess if limited amplitude responses can cause unacceptable stresses or fatigue damage.

NOTE Two types of limited amplitude response can occur:

1) vortex-induced oscillations: these are oscillations of limited amplitude excited by the periodic cross-wind forces arising from the shedding of vortices alternatively from the upper and lower surfaces of the bridge deck. They can occur over one or more limited ranges of wind speeds. The frequency of excitation can be close enough to a natural frequency of the structure to cause resonance and, consequently, cross-wind oscillations at that frequency. These oscillations occur in isolated vertical bending and torsional modes;

2) turbulence response: because of its turbulent nature, the forces and moments developed by wind on bridge decks fluctuate over a wide range of frequencies. If sufficient energy is present in frequency bands encompassing one or more natural frequencies of the structure, vibration can occur.

2.3 Divergent amplitude responses shall be avoided.

2.3.1 Identifiable divergent amplitude aerodynamic mechanisms, leading to oscillations of this type may include:

1) galloping and stall flutter - galloping instabilities arise on certain shapes of deck cross-section because of the characteristics of the variation of the wind drag, lift and pitching moments with angle of incidence or time; and
2) classical flutter - this involves coupling (i.e. interaction) between the vertical bending and torsional oscillations.

2.4 Non-oscillatory divergence shall be avoided.

NOTE Non-oscillatory divergence can occur if the aerodynamic torsional stiffness (i.e. the rate of change of pitching moment with rotation) is negative. At a critical wind speed, the negative aerodynamic stiffness becomes numerically equal to the structural torsional stiffness resulting in zero total stiffness.

2.5 Consistent units shall be used.

NOTE As an example of a consistent set of units, 1 Newton is the force required to accelerate 1 kilogram at $1 m/s^2$.

3. Design for aerodynamic stability

Criteria for applicability and consideration of aerodynamic effects

3.1 Criteria to assess the susceptibility of a bridge to aerodynamic effects shall be in accordance with the NA to BS EN 1991-1-4 [Ref 7.N].

3.1.1 For the purposes of initial/preliminary categorisation, the following may be used to give an indicative range and upper and lower bound values for P_b:

1) $v_m(z)$ between 20 m/s and 40 m/s;
2) $\frac{m}{b}$ between 600 kg/m^2 and 1200 kg/m^2;
3) n_b between $\frac{50}{L^{0.87}}$ and $\frac{100}{L^{0.87}}$, but see also NA to BS EN 1991-1-4 [Ref 7.N], Section NA.2.49.3: NOTE 2.

NOTE 1 b , m , n_b and $v_m(z)$ are defined in NA to BS EN 1991-1-4 [Ref 7.N], Section NA.2.49.2 b).

NOTE 2 L is defined in NA to BS EN 1991-1-4 [Ref 7.N] , Section NA.2.49.3.

Limited amplitude response - vortex excitation

Critical wind speeds for vortex excitation

3.2 Estimates of critical wind speeds ($v_{crit,i}$) at which vortex excitation can occur shall be determined in accordance with the method given in PD 6688-1-4 [Ref 2.N], Section A.1.3.1 and Figure A.2.

Limiting criteria

3.3 Any bridge with a fundamental frequency greater than 5Hz shall be assumed stable with respect to vortex excitation.

3.4 Other criteria used to determine the susceptibility of a bridge to vortex excited vibrations shall be in accordance with PD 6688-1-4 [Ref 2.N], Section A.1.2.

Vortex excitation effects

3.5 Where the bridge cannot be assumed to be aerodynamically stable against vortex excitation, the effects of maximum oscillations of any one of the motions evaluated singly, shall be combined with the effects of other coincident loading (see Section 4).

3.6 Where the bridge cannot be assumed to be aerodynamically stable against vortex excitation, fatigue damage shall be assessed in accordance with Section 5, summed with damage from other fatigue loading.

3.7 The amplitudes of response to vortex excitation shall be determined in accordance with PD 6688-1-4 [Ref 2.N], Section A.1.5.4.1.

3.8 Assessment of the significance of vortex excitation effects shall be determined in accordance with PD 6688-1-4 [Ref 2.N], Section A.1.5.4.5.

Limited amplitude response - turbulence

3.9 To determine whether or not the dynamic magnification effects of turbulence can be neglected, reference shall be made to the NA to BS EN 1991-1-4 [Ref 7.N], Section NA.2.49.2

3.10 Where the magnification effects of turbulence cannot be ignored, a gust buffeting dynamic analysis shall be carried out to calculate the peak amplitudes and modes of vibration under a 10-minute mean wind speed of $v_m(z)$ (as defined in NA to BS EN 1991-1-4 [Ref 7.N], Section NA.2.49.2 b).

3.11 Proximity effects (wake buffeting) shall be evaluated.

3.11.1 Proximity effects should be evaluated using the guidance given in Appendix A.

Divergent amplitude response

3.12 The critical wind speed for each divergent response shall exceed the limiting criteria.

3.13 Estimates of the critical wind speed for galloping and stall flutter for both bending and torsional motion (v_g) and for classical flutter (v_f) shall be derived according to PD 6688-1-4 [Ref 2.N], Section A.2.4.1 and PD 6688-1-4 [Ref 2.N], Section A.4.4 respectively.

3.13.1 Alternatively values of v_g and v_f may be determined by wind tunnel tests (see Section 6).

3.14 The aerodynamic stability of the bridge in respect of divergent responses shall be assessed against the limiting criteria given in PD 6688-1-4 [Ref 2.N], Section A.2.4.2.

3.15 Where the limiting criteria given in PD 6688-1-4 [Ref 2.N], Section A.2.4.2 cannot be satisfied by calculation using the estimates of critical wind speed given in PD 6688-1-4 [Ref 2.N], Section A.2.4.1 and Section A.4.4, the provisions of PD 6688-1-4 [Ref 2.N], Section A.2.4.2 and Section A.4.4.2 shall be used.

4. Partial load factors for aerodynamic design

4.1 The load combinations at ultimate limit state (ULS) and serviceability limit state (SLS) stated in CS 454 [Ref 1.N] shall be modified for aerodynamic effects, as given in Tables 4.5 and 4.6.

4.2 When across-wind vibrations are predicted to occur due to vortex excitation, the corresponding global aerodynamic load effects in the bridge structure shall be calculated for the mode of vibration under consideration, using the maximum amplitude as obtained from Section 3.

4.3 When across-wind vibrations are predicted to occur due to vortex excitation, the along-wind load effects due to mean wind and turbulence shall be calculated, substituting $v_{crit,i}$ for the mode of vibration under consideration as the mean wind speed $v_m(z)$.

4.4 Load effects shall be multiplied by the partial load factor, γ_{fL} .

4.5 For wind loads derived in accordance with CS 454 [Ref 1.N] or turbulence response derived in accordance with Section 3, the partial load factor, γ_{fL} shall be taken from the Table 4.5:

Table 4.5 Partial load factor

Load combination	ULS	SLS
Erection	1.1	1.0
Dead load plus superimposed dead load only, and for members primarily resisting wind loads	1.4	1.0
Appropriate combination 2 loads	1.1	1.0

4.6 For vortex shedding response derived in accordance with Section 3 and combined with any of the cases in Table 4.5, the partial load factor, γ_{fL} shall be taken from Table 4.6.

Table 4.6 Partial load factor

Load combination	ULS	SLS
All	1.2	1.0

4.7 For relieving effects of the wind, γ_{fL} shall be taken as 1.0.

4.8 The factor γ_{fL} on permanent and live loads associated with all load combinations given in Table 4.5 and Table 4.6 shall be as per combination 2 in Table A.1 of CS 454 [Ref 1.N].

NOTE The values of γ_{fL} have been derived for the UK's synoptic wind climate.

5. Fatigue damage

Fatigue damage requirements

5.1 All bridges which fail to satisfy the requirements of Section 3 shall be assessed for fatigue damage due to vortex excited vibration in addition to fatigue damage due to other load effects.

Fatigue damage due to vortex excitation

5.2 An estimate of the cumulative fatigue damage due to vortex excitation shall be made in accordance with BS EN 1993-1-9 [Ref 5.N] by evaluating the stress range and number of cycles specified below, for each model in which $v_{crit,i}$ is less than 1.25 $v_m(z)$.

NOTE *$v_{crit,i}$ is defined in Section 3, and $v_m(z)$ is defined in the NA to BS EN 1991-1-4 [Ref 7.N], Section NA.2.49.2 b).*

5.3 The stress range σ_r shall be taken as 1.2 times the unfactored stress determined from the load effects derived in Section 3.

5.4 The effective number of cycles per year, n , shall be calculated from: $n = 2500f.p.C_\theta.Cs$

NOTE 1 *C_s takes account of the extent of the range of wind speeds over which oscillation can occur.*

NOTE 2 *C_θ is the relative frequency of occurrence of winds within ±10° of normal to the longitudinal centre line of the bridge in strong winds.*

NOTE 3 *f is the natural frequency of the given mode and is taken as n_b for a bending mode or n_t for a torsional mode.*

NOTE 4 *p , C_θ and C_s are given in Figures 5.7a, 5.7b and 5.7c respectively.*

NOTE 5 *p is the frequency of occurrence, in hours per year, of wind speeds within ±2½% of the critical wind speed, $v'_{crit,i}$ below irrespective of direction.*

5.5 The critical wind speed for the estimation of fatigue damage, $v'_{crit,i}$ for all bridge types in PD 6688-1-4 [Ref 2.N] Figure A.3, shall be increased to:

1) $v'_{crit,i}$ = 6.5 for b*/d$_4$ 1.25;
2) $v'_{crit,i}$ = (0.8 b*/d$_4$ + 5.5) f.d$_4$ for 1.25 $\leq$ b*/d$_4$ 10;
3) $v'_{crit,i}$ = 13.5 f.d$_4$ for b*/d$_4$ $\geq$ 10.

5.6 The definitions of b* and d$_4$ shall be taken from Section 3 but noting that d$_4$ is replaced by ϕ d$_4$ for trusses with $\phi 0.5$.

5.7 Alternatively, $v'_{crit,i}$ shall be assessed from wind tunnel tests.

Figure 5.7a Expected frequency of occurrence of critical wind speed (hours per annum of occurrence of speed within +/- 2.5% of critical value)

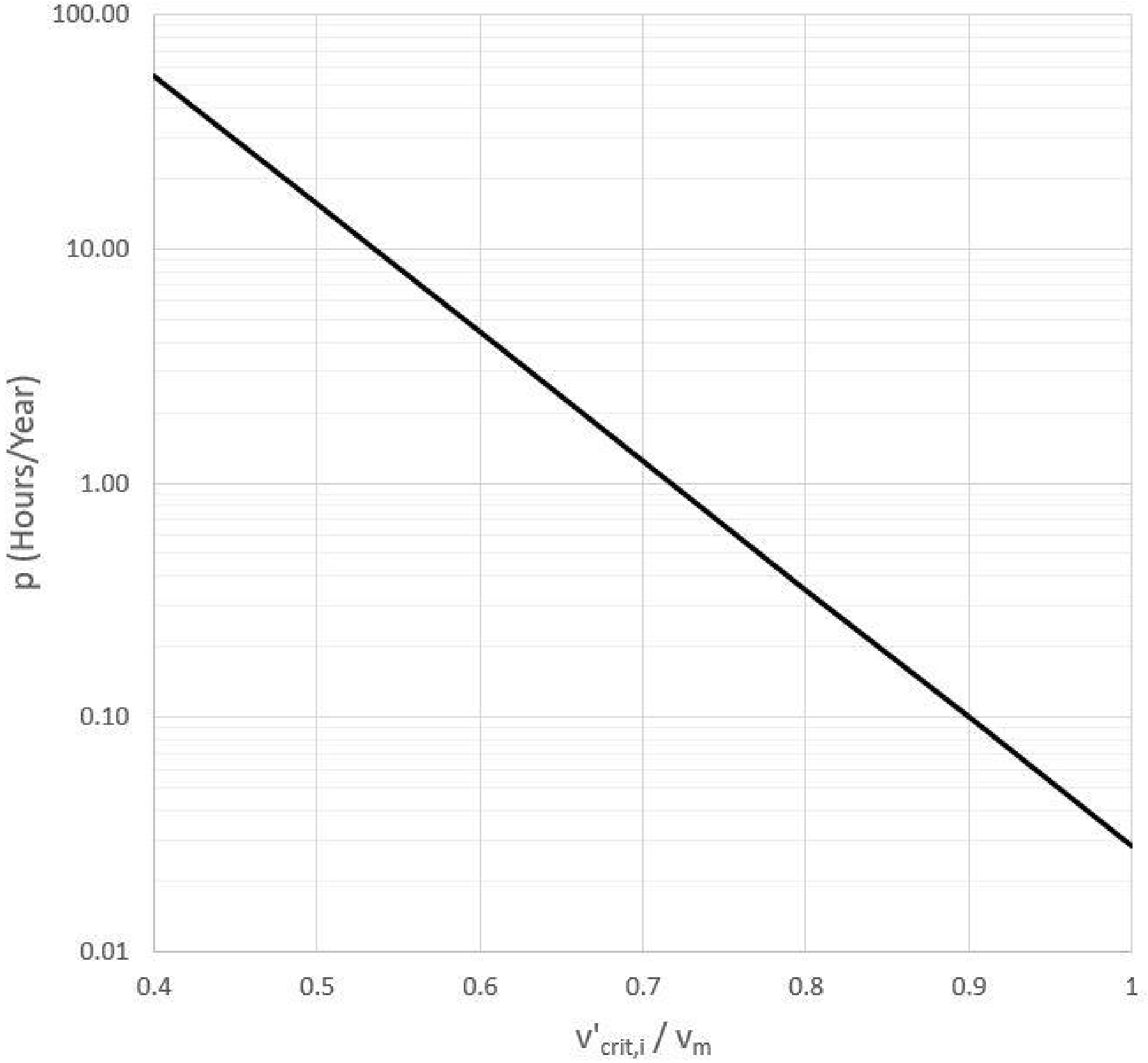


Figure 5.7b Factor for orientation of bridge in plan

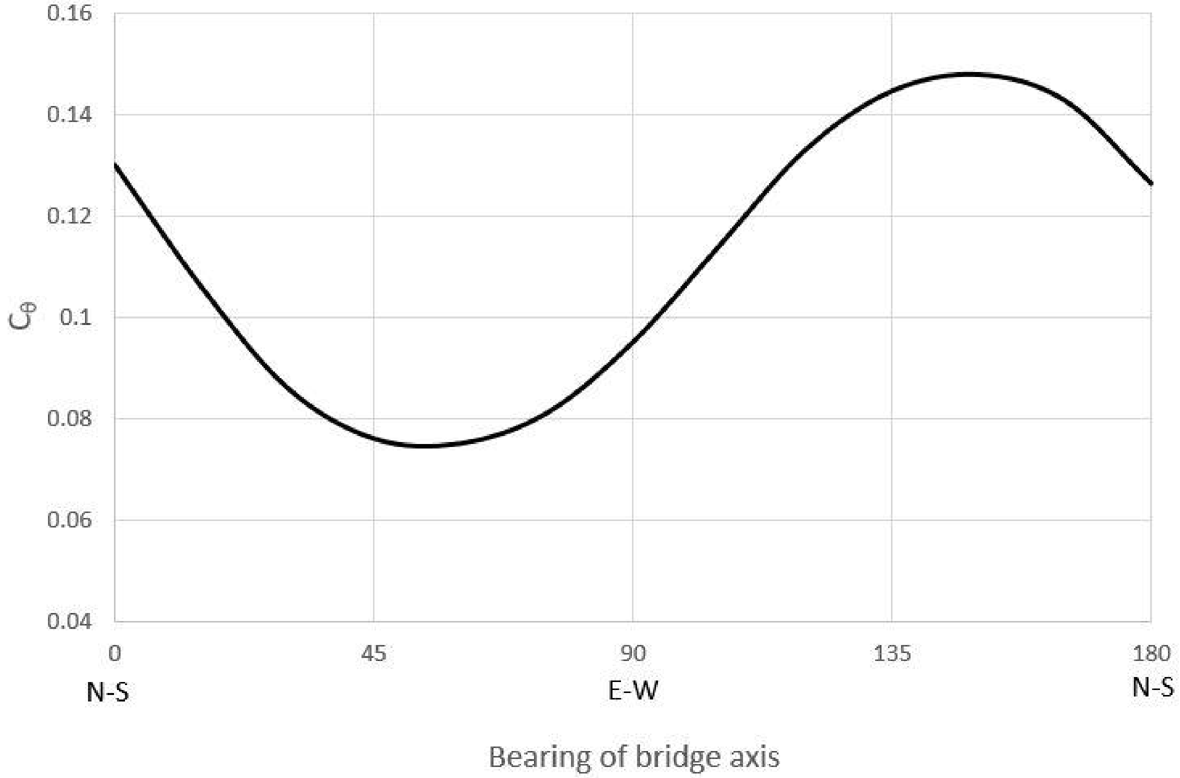
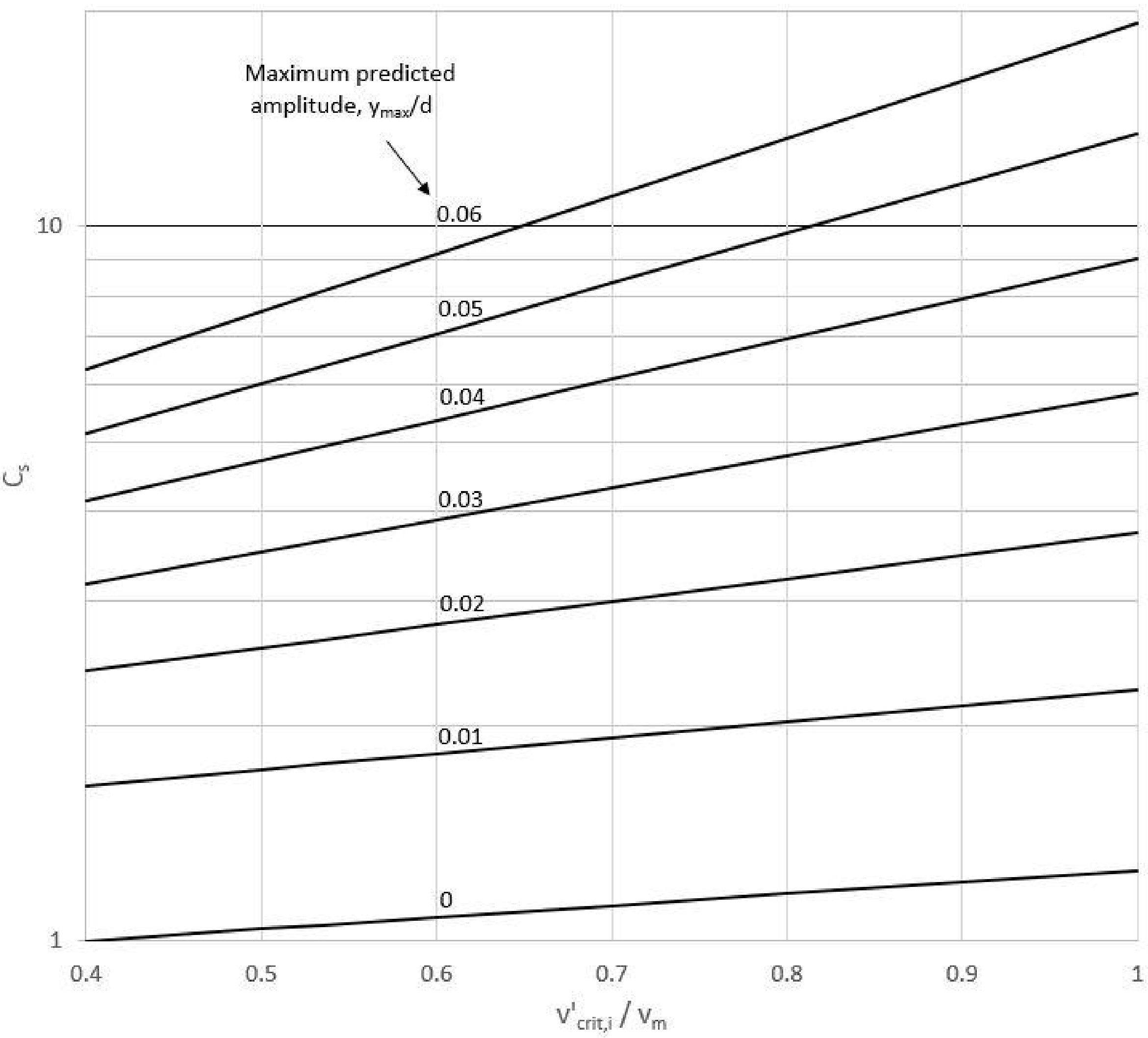


Figure 5.7c Speed range factor



6. Wind tunnel testing

6.1 Where wind tunnel testing is employed, PD 6688-1-4 [Ref 2.N], Section A.5 shall apply.

NOTE Guidelines for wind tunnel testing are given in Appendix B.

7. Proximity effects

7.1 Proximity effects shall be evaluated for twin deck configurations (and adjacent bridges).

NOTE Guidance is given in Appendix A.

8. Normative references

The following documents, in whole or in part, are normative references for this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

Ref 1.N	Highways England. CS 454, 'Assessment of highway bridges and structures'
Ref 2.N	BSI. PD 6688-1-4, 'Background information to the National Annex to BS EN 1991-1-4 and additional guidance'
Ref 3.N	BSI. BS EN 1991-1-4, 'Eurocode 1: Actions on structures. Part 1-4: General actions – Wind actions'
Ref 4.N	BSI. BS EN 1993-2, 'Eurocode 3. Design of steel structures Part 2: Steel bridges'
Ref 5.N	BSI. BS EN 1993-1-9, 'Eurocode 3. Design of steel structures. Fatigue.'
Ref 6.N	Highways England. GG 101, 'Introduction to the Design Manual for Roads and Bridges'
Ref 7.N	BSI. NA to BS EN 1991-1-4, 'UK National Annex to Eurocode 1 - Actions on structures: Part 1-4: General actions - Wind actions'

9. Informative references

The following documents are informative references for this document and provide supporting information.

Ref 1.I	Transport Research Laboratory. Flint & Neill Partnership. TRL CR256, 'A re-appraisal of certain aspects of the design rules for bridge aerodynamics. TRL Contractor Report 256 (1992)'
Ref 2.I	Thomas Telford Limited. ICE 1981, 'Bridge aerodynamics. Proceedings of Conference at the Institution of Civil Engineers (1981)'
Ref 3.I	Transport Research Laboratory, Crowthorne. Flint & Neill Partnership. TRL CR36, 'Partial safety factors for bridge aerodynamics and requirements for wind tunnel testing. TRL Contractor report 36'
Ref 4.I	Archived results: Library of Institution of Civil Engineers. Library of Institution of Civil Engineers. ICE Box Girders, 'Wind tunnel tests on box girders and plate girder bridges'
Ref 5.I	TRL. Flint & Neill Partnership in association with BMT Fluid Mechanics Limited and TRL (290/2/3/96, May 1996). TRL RR530, 'Wind tunnel tests on plate girder bridges (subsequently published as TRL report 530 in 2002)'

Appendix A. Guidance on proximity effects

A1 Introduction

Most obstacles in the path of the wind contribute to the creation of turbulence, either directly by vortex shedding or indirectly through the build-up of the profile of mean wind speed with height which in turn provides more severe velocity differentials when the flow is further perturbed. The basic turbulence is the statistically steady (or developing slowly over a distance of many kilometres) summation of the effect of a broadly random scatter of such obstacles over a substantial region upwind of the reference point. Where there are identifiable outstanding obstacles, further specific allowance may be necessary.

The turbulence generated by such identifiable objects decays on translation downwind into a more random structure comprising a widening range of gust sizes (or spectral frequencies), eventually being subsumed into the basic random 'background'. There is thus a range of potential effects. Where there are obstacles (topographic or man-made) that are large compared with the cross-section of the bridge, wind tunnel tests can be used to check on the consequences of any change in turbulence affecting the bridge.

A parallel, or near-parallel, prismatic obstacle such as another bridge should be included in any wind tunnel tests. However, where the gap is small compared to the characteristic dimension of the 'vortex street' (say, less than the structure depth) the formation and shedding of vortices become strongly linked. Assessments for small and moderate separation are given below.

A2 Twin-deck configurations

The term 'twin-deck bridge' is used here to describe a bridge with parallel decks each supported by the same structural form with equal structural depth, with a gap between the decks not exceeding one metre, and the deck edges bordering the gap (or each gap) not differing in level by more than 250 mm. The gap may be closed by an apron, or left open. The deck cross-falls may be in the same sense or reversed.

A3 Evaluation of parameters for vortex shedding

For the evaluation of the critical wind speed for vortex excitation (see Section 3), the reference width b^* should be determined according to PD 6688-1-4 [Ref 2.N] Figure A.4, applied to the overall cross-section ignoring the existence of the gap when the gap complies with the twin-deck configuration in A2 above. For all other provisions in this Appendix A, the evaluations should be based on the parameters for the upwind deck. Additionally, the prediction made of response amplitude $y_{\max}$ for vertical motion caused by vortex shedding (see Section 3) should be increased by a factor of 1.4 to conservatively allow for the interactive response of the twin-deck system.

Where the gap exceeds G_2 (see A4 below) each bridge deck may be treated separately with respect to vortex excitation. For gaps in the ranges of G_1 to G_2 (see A4 below), the estimate of the limiting response amplitude to vortex shedding, $y_{\max}$, given in Section 3 should be doubled. For gaps between 1m and G_1 (see A4 below) for twin deck configurations and less than G_1 (see A4 below) for all other configurations, the interactive vortex response of the dual system should be investigated.

A4 Other proximity effects

The limiting value of P(z) as defined in NA to BS EN 1991-1-4 [Ref 7.N], Clause 2.49.2 should be halved if there is a parallel structure with a clear gap G such that $G_1 < G < G_2$, where:

G_1 is the lesser of d' or $\frac{b'}{3}$; and

G_2 is the greater of $24d'$ or $6b'$

in which d' and b' are the overall depth and breadth respectively of the neighbouring structure.

Where the gap is less than G_1 the parallel structures may be considered as a single structure for turbulence effects.

Where the gap is greater than G_2 , turbulence effects may be considered independently on each structure.

Appendix B. Guidelines for wind tunnel testing

B1 Introduction

This appendix provides some guidelines to assist the engineer who intends to make use of wind tunnel model testing. These guidelines should not be regarded as complete as testing techniques are continually being developed. Other publications should be referred to for more extensive details of the theory and practice of wind tunnel testing.

In providing relatively comprehensive procedures it is recognised that sometimes it becomes necessary to relax modelling requirements in order to obtain practical information. It is important to stress the need for an awareness of the limitations of wind tunnel model tests in general with special caution in situations where partial or approximate models are used.

There are three basic reasons for undertaking wind tunnel tests:

1) to obtain static coefficients to be used in the basic static design checks for wind or for input to the analysis of turbulence response (see Section 3);
2) to obtain coefficients for checks on vortex excitation effects or divergent amplitude effects (see Section 3). Such tests require dynamic models, and can also yield either direct estimation of turbulence response or 'derivative' coefficients which enable more sophisticated analysis of turbulence response to be carried out;
3) to examine the influence of topography or other perturbations of the incident wind such as large structures or other obstacles nearby. A potentially important effect is inclination of the mean wind to the horizontal (quantity $\overline{\alpha}$ in PD 6688-1-4 [Ref 2.N], Section A.5).

Aeronautical wind tunnels (wind tunnels operating with laminar flow) are typically used for large scale models to accurately simulate the structure, deck furniture and highway or railway traffic. More accurate measurements of mean loads require a simulation of the turbulence characteristics of wind, but this requires a model whose scale is too small to be practicable. Smooth flow tests are thus generally acceptable for these measurements providing upper bound values to the coefficients when compared to those appropriate to the natural wind.

Studies into the influence of topography or other perturbations of the incident wind require simulation of the salient properties of the wind. Wind tunnels designed to develop this type of flow are classified as boundary-layer wind tunnels (BLWT). The required small scale of the topography is such that a realistic model of the bridge itself is impracticable.

Both types of wind tunnel use air at atmospheric pressure and operate in a low-speed range of 10-50 m/s.

Where relevant, proximity effects need to be considered and adjacent structures modelled (see Appendix A).

B2 Use of smooth flow (laminar) tests to determine time average coefficients

Tests on sectional models of bridge decks can be used to determine the mean or static components of the overall wind load on the model. These wind loads can be obtained using rigid models with geometrically scaled features.

Accurate measurements of both the mean and the dynamic components of the overall loads can only be obtained if both the approach flow and the local environment are properly simulated. For the scale of model bridge required, this becomes impracticable.

Approaches towards evaluating overall wind loads include the spatial averaging of instantaneous pressures acting on the elements of the bridge structure and the direct measurement of such loads with force balances or transducers capable of providing accurate information on both their mean and time-varying components. Sections comprising circular section members or other curved surfaces are likely to be Reynolds number (R_e) -sensitive and adjustments based on full-scale data and/or theoretical data may be used. Modelling adjustments are commonly needed for very small elements such as handrails to avoid local R_e effects below about 500.

The effect of wind inclination in elevation should be examined. The extent of the effect should be judged depending on the site topography, any planned super-elevation of the bridge and predicted torsional deflections under traffic loads. Generally tests up to ±5° are adequate.

B3 Section model tests to determine aerodynamic stability

The primary objective of section model tests is to determine the aerodynamic stability of the bridge deck, mounted with deck furniture, using a geometrically scaled model of a section of the bridge elastically mounted in a wind tunnel. Typically, such models simulate the lowest bending and torsional vibration frequencies, and are tested in uniform laminar flow. The requirements of geometric scaling and Reynolds number limitations, outlined in B2, still apply. In more advanced or refined stages, section models are tested in simulated turbulent flow in order to provide estimates of the responses at sub-critical wind speeds. As the simulated turbulence generally has a preponderance of the smaller-size eddies most likely to influence flow features such as vortex-shedding or re-attachment, the total intensity of turbulence should be selected with care. Generally this should be significantly lower than the standard atmospheric value for full scale. Reliance on beneficial effects from turbulence should not be allowed to reduce the likely aerodynamic effects.

In addition to modelling the geometry in accordance with B2, it is necessary to maintain a correct scaling of inertia forces, the time scale, the frequency, and the structural damping. The time scale is normally set indirectly by maintaining the equality of the model and full-scale reduced velocities of particular modes of vibration. The reduced velocity is the ratio of a reference wind speed and the product of a characteristic length and the relevant frequency of vibration. See v_{Rg} and v_{Rf} in PD 6688-1-4 [Ref 2.N], A.2.4.1 and A.4.4 for 'galloping' and 'flutter'. The numerical coefficient for vortex excitation in Section 3 is also derived from use of a similar ratio.

Measurements should be carried out through the range of wind speeds likely to occur at the site to provide information on both relatively common events, influencing serviceability, and relatively rare events, which govern ultimate strength behaviour. Wind inclination in elevation should be examined. Measurements of vortex excitation require careful control of the wind speed around the critical velocity, and any predicted divergent amplitudes should be assessed to ensure they do not become so violent as to destroy the model.

B4 Aero-elastic simulations of bridges

A dynamic model of the full bridge should be used in the wind tunnel, commonly referred to as an aero-elastic model, to provide information on the overall wind induced mean and/or dynamic loads and responses of bridges. Such models are particularly valuable for slender, flexible and dynamically sensitive structures, where dynamic response effects may be significant. To be representative the tests should consistently model the salient characteristics of natural wind at the site and the aerodynamically significant features of the bridge's geometry. It is also necessary to correctly model the stiffness, mass and damping properties of the structural system.

It is only possible to model the full spectrum of atmospheric turbulence in a wind tunnel at small scale; together with the obvious constraint of fitting a full bridge model within the tunnel, this is generally irreconcilable with the scale desirable to ensure correct behaviour, which is commonly sensitive to small changes in cross-section. For this reason the primary study should be made by section model tests; where non-uniformity of section or of incident flow conditions, complex dynamics or erection considerations, necessitate the use of a full model, particular care is needed in its design and interpretation of the test results.

As the modelling of dynamic properties requires the simulation of the inertia, stiffness and damping characteristics of only those modes of vibration which are susceptible to wind excitation, approximate or partial models of the structural system are often sufficiently accurate.

B5 Studies of the wind environment

B5.1 Topographic models

Information on the characteristics of the full scale wind may not be available in situations of complex topography and/or terrain. Small scale topographic models, with scales in the range of 1:2000, can be used in such situations to provide estimates of the subsequent modelling of the wind at a larger scale and are suitable for studying particular wind effects on the bridge.

B5.2 Local environment

Nearby buildings, structures, and topographic features of significant relative size influence the local wind flow and hence should be allowed for in simulations of wind at particular locations. For bridges in urban settings this requires the scaled reproduction (usually in block outline form) of all major buildings and structures within about 500 to 800 m of the site. Also of particular importance is the inclusion of major nearby existing and projected buildings, which can lead to aerodynamic interference effects, even if they are outside this "proximity" model.

Corrections are generally required if the blockage of the wind tunnel test section by the model and its immediate surroundings exceeds 5 to 10%. Typical geometric scales used in studies of overall wind effects or for local environment tests range between 1:300 to 1:600 approximately.

B5.3 Use of boundary layer wind tunnels (BLWT)

A BLWT should be capable of developing flows representative of natural wind over different types of full-scale terrain. The most basic requirements are as follows:

1) to model the vertical distribution of the mean wind speed and the intensity of the longitudinal turbulence; and,
2) to reproduce the entire atmospheric boundary layer thickness, or the atmospheric surface layer thickness, and integral scale of the longitudinal turbulence component to approximately the same scale as that of the modelled topography.

In some situations a more complete simulation including the detailed modelling of the intensity of the vertical components of turbulence becomes necessary.

B6 Instrumentation

The instrumentation used in wind tunnel model tests of all aforementioned wind effects should be capable of providing adequate measures of the mean and, where necessary, the dynamic or time varying response over periods of time corresponding to about 1 hour in full scale. In the case of measurements of wind induced dynamic effects, overall wind loads and the response, the frequency response of the instrumentation system should be sufficiently high to permit meaningful measurements at all relevant frequencies, and avoid magnitude and phase distortions.

All measurements should be free of significant acoustic effects, electrical noise, mechanical vibration and spurious pressure fluctuations, including fluctuations of the ambient pressure within the wind tunnel caused by the operation of the fan, opening of doors and the action of atmospheric wind. Where necessary, corrections should be made for temperature drift.

Most current instrumentation systems are highly complex and include on-line data acquisition capabilities which in some situations are organised around a computer which also controls the test. It may be possible to provide useful information with more traditional techniques including smoke flow visualisation. Although difficult to perform in turbulent flow without proper photographic techniques, flow visualisation remains a valuable tool for evaluating the overall flow regime and, in some situations, on the potential presence of particular aerodynamic loading mechanisms.

B7 Quality assurance

The reliability of all wind tunnel data should be established and should include considerations of both the accuracy of the overall simulation and the accuracy and hence the repeatability of the measurements. Checks should be devised where possible to assure the reliability of the results. These should include basic checking routines of the instrumentation including its calibration, the repeatability of particular measurements and, where possible, comparisons with similar data obtained by different methods. For example, mean overall force and/or aero-elastic measurements can be compared with the integration of mean local pressures.

Ultimate comparisons and assurances of data quality can be made in situations where full-scale results are available. Such comparisons are not without difficulties as both the model and full-scale processes are stochastic. It is also valuable to make credibility crosschecks with the code requirements and previous experience.

B8 Interpretation of test data and prediction of full-scale behaviour

The objective of all wind tunnel simulations is to provide direct or indirect information on wind effects during particular wind conditions.

For time average effects this relates to the appropriate design wind speed either with or in the absence of traffic as appropriate. Dynamic response requires prediction of the full-scale wind speeds at which vertical and/or torsional vortex excitation occurs as well as the speed at which divergent response is likely to start.

Particular care is required in relation to simulation and scaling such as, for example, with respect to wind speed, turbulence (intensity and length scales), frequency and damping (see B2, B3 and B5) as well as the bridge geometry and properties (see B4). The range of wind angles considered needs to take due account of the requirements in PD 6688-1-4 [Ref 2.N] Section A.5. Where measurements have been undertaken in turbulent flow (see B3 and B4), the intensity of turbulence and associated length scales need to be reported for both the reduced and full size intensities and length scales.

B9 Typical scales

The following typical scales for the various types of wind tunnel tests are recommended:

Table B.1 Recommended scales for different wind tunnel tests

Type of test	Typical scale
Topographic models	1:2000
Local environment	1:600 to 1:300
Aero-elastic models	1:200 to 1:100
Section models (stability or time average coefficients)	1:80 to 1:40
Models of ancillaries	>1:20