Design Manual for Roads and Bridges

Highway Structures & Bridges
Design

CD 360
Use of compressive membrane action in bridge decks

(formerly BD 81/02)

Revision 2

Summary
This document provides requirements and advice for the use of compressive membrane action in the design and assessment of reinforced concrete bridge deck slabs.

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.

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Release notes

Version	Date	Details of amendments
2	Mar 2020	Revision 2 (March 2020) Revision to update references only. Revision 1 (October 2018) This revision reflects a minor change to a typographical error in clause 4.2. Clause 4.2 now reads as a requirement with 11 sub points and two corresponding notes. Revision 0 (June 2018) CD 360 replaces BD 81/02. This full document has been re-written to be compliant with the new Highways England drafting rules.

Foreword

Publishing information

This document is published by Highways England.

This document supersedes BD 81/02, which is withdrawn.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

This document provides requirements and advice for the use of the compressive membrane action in the design and assessment of reinforced concrete bridge deck slabs.

Flexure of unrestrained slabs is associated with in-plane movements at the supports which are compatible with the vertical deflections of the slab. However, if these movements are restrained effectively, a system of compressive forces can be established which carries the load in an arching action. This behaviour is known as compressive membrane action and can significantly increase the load capacity of the slab.

Several studies have shown the beneficial effects of the compressive membrane action to the strength of reinforced concrete deck slabs where sufficient restraints exist. Many of the criteria given in this document are based on experimental evidence, which has been conservatively interpreted for use in the design and assessment. A summary of the most recent research and testing can be found in 'A review of arching and compressive membrane action in concrete bridges' Collings & Sagaseta [Ref 1.I].

Assumptions made in the preparation of this document

The assumptions made in GG 101 [Ref 5.N] apply to this document.

Symbols

Symbols

Symbol	Definition
d	Average effective depth to the tensile reinforcement (mm)
ε_c	Plastic strain of an idealised elastoplastic concrete (non-dimensional)
f_c	Concrete compressive cylinder strength (N/mm^2)
$f_{ck,cube}$	Characteristic compressive cube strength as defined in BS EN 1992-1-1 [Ref 4.N] (N/mm^2)
f_{cu}	Characteristic or worst credible concrete cube strength as defined in CS 455 [Ref 6.N] (N/mm^2)
h	Overall slab depth (mm). For precast concrete participating formwork panels h is taken as the overall depth minus 10 mm, in order to allow for the reduced depth at panel joints.
k	Arching moment coefficient (non-dimensional)
L_r	Half span of slab strip with boundary restraint (mm)
P_{pd}	Ultimate predicted load (axle loading)
P_{ps}	Ultimate predicted load (per wheel)
R	Arching moment of resistance (non-dimensional)
γ_c	Partial factor for concrete (non-dimensional) in accordance with BS EN 1992-1-1 [Ref 4.N]
γ_m	Partial safety factor for strength (non-dimensional) in accordance with CS 455 [Ref 6.N]
φ	Diameter of loaded area (mm)

Terms and definitions

Terms

Term	Definition
Boundary restraint	Restraint generated around the boundary of a deck slab by adjacent members and which can be assumed to limit the in-plane expansion of a deck member.
Span of slab strip	Primary span. This is taken as: 1. clear span in slabs monolithic with beams; or 2. distance between beam web centre lines in slabs supported on steel or concrete girders.

1. Scope

Aspects covered

1.1 This document shall be used in conjunction with the of DMRB document CS 455 [Ref 6.N] and BS EN 1992-2 [Ref 3.N] except where otherwise required by this document.

1.2 This document shall be used for the design and assessment of reinforced concrete bridge deck slabs subject to single wheel and axle loading.

1.3 During the design and assessment of reinforced concrete bridge deck slabs, the slab shall be checked under both global and local loading cases.

1.3.1 Flexural action should be assumed in analysing slabs.

1.4 Bridge deck slabs shall be restrained along all four boundaries, as defined in clause 4.2, in order for compressive membrane action to be reliably mobilised.

1.5 This document shall be used for steel and concrete beam and slab type bridge decks, including those with participating precast concrete deck slab formwork.

1.6 This document shall not be used for cantilever overhangs nor deck slabs with insufficient restraint, which shall be designed or assessed in accordance with BS EN 1992-2 [Ref 3.N] and CS 455 [Ref 6.N].

1.7 Loadings shall be in accordance with DMRB document CS 454 [Ref 1.N] for assessment and BS EN 1991-2 [Ref 2.N] for design.

Implementation

1.8 This document shall be implemented forthwith on all schemes involving the use of compressive membrane action for design and assessment in bridge decks with sufficient restraint on the Overseeing Organisations' motorway and all-purpose trunk roads according to the implementation requirements of GG 101 [Ref 5.N].

Use of GG 101

1.9 The requirements contained in GG 101 [Ref 5.N] shall be followed in respect of activities covered by this document.

2. Design

General

2.1 Reinforced concrete bridge deck slabs shall be designed in accordance with BS EN 1992-2 [Ref 3.N] and this document.

2.2 Individual primary and secondary elements shall be designed to resist the loading which produces the most adverse effects due to combined global and local effects, where they coexist, in addition to the loading directly applied to them.

2.3 Analysis of the structure shall be carried out by separate analyses for global and local effects.

Serviceability limit state

2.4 In order to allow for the effects of compressive membrane action on the global load distribution, two separate analyses shall be carried out using the flexural stiffness constants (second moment of area) for sections of discrete members or unit widths of slab elements as follows:

1) Design of members spanning in the direction of compressive membrane action (i.e. the deck slab in beam and slab construction): the entire member cross-section, ignoring the reinforcement, for all members.
2) Design of members spanning in the other direction (i.e. the longitudinal beams in beam and slab construction): half of the member cross-sectional width, ignoring the reinforcement, for the member subject to compressive membrane action (i.e. the deck slab), and the full member cross-sectional width, ignoring the reinforcement, for the other members (i.e. longitudinal beams).

2.4.1 The deck slab may be designed for twice the moment given by analysis 2 above, in order to avoid the need to undertake two separate analyses.

2.5 For reinforced concrete bridge deck slab panels restrained as defined in 4.2, the crack width due to global effect only shall be determined in accordance with BS EN 1992-2 [Ref 3.N].

Ultimate limit state

2.6 Elastic method shall be used to determine the distribution of forces, as stated in 2.4.

2.7 Where the slabs comply with all the limitations of 4.2, the empirical method given in 4.3 to 4.12 shall be used for local analysis.

2.8 Where reinforced concrete bridge deck slabs are restrained as defined in 4.2, the deck slab reinforcement shall be derived on the basis of global effects only, in accordance with BS EN 1992-2 [Ref 3.N].

2.9 The resistance to local effects shall be derived from the formulae in clauses 4.3 to 4.12.

NOTE Punching shear is taken account of through the procedures presented in this document.

Minimum area of reinforcement

2.10 The minimum steel area provided in the deck slab in each face in each direction shall be 0.3% of the gross concrete section.

2.11 The spacing of the bars shall be not greater than 250 mm.

2.12 The reinforcement in both faces in the direction of the primary slab span shall not be less than 750 mm^2 /m.

2.13 Where longitudinal reinforcement is required to resist global effects (e.g. in continuous bridges), the nominal steel required by clause 2.10 shall be provided in addition to the steel required to resist global effects.

2.14 Not less than 30% of the steel required for global effects shall be placed in the bottom face of the slab.

3. Assessment

General

3.1 Reinforced concrete bridge deck slabs shall be assessed in accordance with DMRB document CS 455 [Ref 6.N] and this document.

3.2 Individual primary and secondary elements shall be designed to resist the loading that produces the most adverse effects due to combined global and local effects, where they coexist, in addition to the loading directly applied to them.

3.3 Analysis of the structure shall be carried out by separate analyses for global and local effects.

3.4 The assessed local capacity of the deck shall not exceed the load carrying capacity of adjacent supporting members.

Ultimate limit state

3.5 In order to allow for the effects of compressive membrane action on the global load distribution, two separate analyses shall be carried out using the flexural stiffness constants (second moment of area) for sections of discrete members or unit widths of slab elements as follows:

1) Assessment of members spanning in the direction of compressive membrane action (i.e. the deck slab in beam and slab construction): the entire member cross-section, ignoring the reinforcement, for all members.
2) Assessment of members spanning in the other direction (i.e. the longitudinal beams in beam and slab construction): half of the member cross-sectional width, ignoring the reinforcement, for the member subject to compressive membrane action (i.e. the deck slab), and the full member cross-sectional width, ignoring the reinforcement, for the other members (i.e. longitudinal beams).

3.5.1 The deck slab may be assessed for twice the moment given by analysis 2 above, in order to avoid the need to undertake two separate analyses.

3.6 Where the slabs comply with all the limitations of 4.2, the empirical method given in clauses 4.3 to 4.12 shall be used for local analysis.

3.7 Where in addition to complying with all the limitations of clause 4.2 the slab is at least 160 mm and has a characteristic or worst credible concrete cube strength (f_{cu}) of 40 N/mm^2, a HB loading of up to 45 units shall be assumed for local analysis.

3.8 Where reinforced concrete bridge deck slabs are restrained as defined in 4.2, the global resistance shall be derived from all of the member reinforcement, in accordance with CS 455 [Ref 6.N].

3.9 The resistance to local effects shall be derived from 4.3 to 4.12.

NOTE *Punching shear is taken account of through the procedures presented in this document.*

4. Calculation of local capacity of bridge deck slabs

General

4.1 The following method shall be used to calculate the ultimate local capacity of laterally restrained deck slabs for design and assessment.

NOTE This method assumes that the slab reinforcement makes no contribution to the local load carrying capacity.

Limitations

4.2 The procedures given in clauses 4.3 to 4.12 shall only be used for design and assessment of bridge deck slabs that comply with the following limitations:

1) The transverse (primary) span length of a slab panel perpendicular to the direction of traffic does not exceed 3.7 m.
2) The slab extends at least 1.0 m beyond the centre line of the external longitudinal supports of a panel.
3) The span length to thickness ratio of the slab does not exceed 15.
4) In skew slabs, the skew span length to thickness ratio does not exceed 15.
5) For skew angles greater than 20°, the end portion of the deck is designed or assessed in accordance with BS EN 1992-2 [Ref 3.N] or CS 455 [Ref 6.N] respectively.
6) Transverse edges at the ends of the bridge and at intermediate points where the continuity of the slab is broken are both supported by diaphragms or other suitable means and are designed for the full effects of the wheel loads.
7) Cross frames or diaphragms are present at the support lines of all bridges.
8) Bridges with steel beams also have cross frames or diaphragms at centres not exceeding 8 m or half of the span of the bridge.
9) Bridges with concrete beams, other than prestressed beams complying with the serviceability imitations of BS EN 1992-2 [Ref 3.N] for design and CS 455 [Ref 6.N] for assessment, have at least one intermediate diaphragm in each span.
10) All the cross frames or diaphragms extend throughout the width of the bridge between external girders and extend from the top to the bottom flange, or in case of T section beams with no distinct bottom flange, from the slab over at least 75% of the depth of the web.
11) Edge beams are present for all slabs having main reinforcement parallel to traffic.

NOTE 1 Where in an external panel the combined cross-sectional area of slab and kerb, beyond the centre line of the external girder, is not less than the cross-sectional area of one metre length of deck slab, (referred to in item 2 in the list above) a kerb or string course integral with the slab can be used instead of the 1.0 m overhang.

NOTE 2 An edge beam (referred to in item 11 in the list above) can consist of a slab section reinforced to carry the full effect of wheel loads, a beam integral with and deeper than the slab, an integral reinforced section of slab and kerb, or a continuous parapet or barrier to stiffen the edge of the slab.

Procedure

4.3 The concrete compressive cube strength shall be expressed as the equivalent cylinder strength $f_c(N/mm^2)$ given by Equation 4.3a for assessment and Equation 4.3b for design.

Equation 4.3a Assessment

$$f_c = \frac{0.8 f_{cu}}{\gamma_m}$$

Equation 4.3b Design

$$f_c = \frac{0.8 f_{ck,cube}}{\gamma_c}$$

4.4 The plastic strain of an idealised elastic-plastic concrete, ε_c , shall be taken as:

Equation 4.4

$$\varepsilon_c = \left(-400 + 60 f_c - 0.33 f_c^2\right) 10^{-6}$$

4.5 The non-dimensional parameter for arching moment of resistance, R , shall be taken as:

Equation 4.5

$$R = \frac{\varepsilon_c L_r^2}{h^2}$$

4.6 Where R is less than 0.26, the deck slab shall be treated as restrained.

4.7 Where R is higher than 0.26, the deck slab shall be treated as unrestrained.

4.8 Where R is higher than 0.26, benefit from compressive membrane action to enhance the load capacity of the slab shall not be assumed.

4.9 The non-dimensional arching moment co-efficient, k , shall be taken as:

Equation 4.9

$$k = 0.0525\left(4.3 - 16.1\sqrt{3.3 \times 10^{-4} + 0.1243R}\right)$$

4.10 The effective reinforcement ratio, ρ_e , shall be taken as:

Equation 4.10

$$\rho_e = k\left[\frac{f_c}{240}\right]\left[\frac{h}{d}\right]^2$$

4.11 The ultimate predicted load for a single wheel, $P_{ps}(N)$, shall be taken as:

Equation 4.11

$$P_{ps} = 1.52(\varphi + d)d\sqrt{f_c}(100\rho_e)^{0.25}$$

4.12 Where a deck is subject to axle loading, either two wheels on one slab or two wheels on adjacent axles, the ultimate predicted wheel load, $P_{pd}(N)$, shall be taken as:

Equation 4.12

$$P_{pd} = 0.65 P_{ps}$$

5. 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. BS EN 1991-2, 'Eurocode 1. Actions on structures. Traffic loads on bridges'
Ref 3.N	BSI. BS EN 1992-2, 'Eurocode 2. Design of concrete structures. Part 2: Concrete bridges. Design and detailing rules'
Ref 4.N	BSI. BS EN 1992-1-1, 'Eurocode 2: Design of concrete structures. General rules and rules for buildings'
Ref 5.N	Highways England. GG 101, 'Introduction to the Design Manual for Roads and Bridges'
Ref 6.N	Highways England. CS 455, 'The assessment of concrete highway bridges and structures'

6. Informative references

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

Ref 1.I	Proceedings of the Institution of Civil Engineers Bridge Engineering 169(4):271-284. Collings, D. and Sagaseta, J. Collings & Sagaseta, 'A review of arching and compressive membrane action in concrete bridges'