CORRECTIONS WITHIN DESIGN MANUAL FOR ROADS AND BRIDGES
MAY 2007

SUMMARY OF CORRECTION – BD 81/02 Volume 3, Section 4, Part 20
USE OF COMPRESSIVE MEMBRANE ACTION IN BRIDGE DECKS

Corrections have been made to Chapter 4 – para 4.4 reference to ‘4.14’ changed to ‘3.13 - 3.14’.

We apologise for the inconvenience caused.

Highways Agency
May 2007

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VOLUME 3 HIGHWAY STRUCTURES: INSPECTION AND MAINTENANCE

SECTION 4 ASSESSMENT

PART 20

BD 81/02

USE OF COMPRESSIVE MEMBRANE ACTION IN BRIDGE DECKS

SUMMARY

This Departmental Standard specifies design and assessment criteria for reinforced concrete bridge deck slabs.

INSTRUCTIONS FOR USE

This is a new Standard to be incorporated in the Manual.

1. Remove existing contents page for Volume 3, and insert new contents page for Volume 3, dated May 2002.

2. Insert BD 81/02 in Volume 3, Section 4, Part 20.

3. Archive this sheet as appropriate.

Note: A quarterly index with a full set of Volume Contents Pages is available separately from The Stationery Office Ltd.

THE HIGHWAYS AGENCY

SCOTTISH EXECUTIVE DEVELOPMENT DEPARTMENT

THE NATIONAL ASSEMBLY FOR WALES
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THE DEPARTMENT FOR REGIONAL DEVELOPMENT
NORTHERN IRELAND

Use of Compressive Membrane Action in Bridge Decks

Summary: This Departmental Standard specifies design and assessment criteria for reinforced concrete bridge deck slabs.

REGISTRATION OF AMENDMENTS

Amend No	Page No	Signature & Date of incorporation of amendments	Amend No	Page No	Signature & Date of incorporation of amendments
Correction No 1	**5/1 – 5/2**	**August 2002**			
Correction No 2	**4/1 – 4/2**	**May 2007**			

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PART 20

BD 81/02

USE OF COMPRESSIVE MEMBRANE ACTION IN BRIDGE DECKS

Contents

1. INTRODUCTION AND IMPLEMENTATION

General

1.1 This Standard relates to the use of compressive membrane action in the design and assessment of reinforced concrete bridge deck slabs. It shall be used in conjunction with the relevant parts of BD 24 and BD 44 except where otherwise specified by this Standard.

Implementation

1.2 This Standard shall be used for the design and assessment of reinforced concrete bridge deck slabs. Design and assessment organisations shall confirm its application to particular bridges with the Technical Approval Authority.

1.3 This Standard is intended for use in the design and assessment of reinforced concrete bridge deck slabs which have sufficient restraint to benefit from compressive membrane action.

Scope

1.4 This Standard specifies criteria and methods for the design and assessment of reinforced concrete bridge deck slabs subject to single wheel and axle loading.

1.5 Methods are presented for both simplified and rigorous methods of analysis. Limitations are presented in 2.6 and 5.10 for the use of the simplified method.

1.6 The detailed procedure for undertaking the non-linear finite element analysis of a concrete structure is beyond the scope of this Standard.

Implementation

1.7 This Standard shall be used for the design and assessment of highway bridges to ultilise the beneficial effects of membrane action where adequate deck slab restraint exists.

Definitions

1.8 The meaning and definition of terms used shall generally be in accordance with BS 6100, unless otherwise defined below:

Boundary Restraint

This is the 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

This is the primary span and shall be taken as:

Slabs monolithic with beams: clear span

Slabs supported on steel or concrete girders: distance between beam web centre lines

2. GENERAL PRINCIPLES

General

2.1 During the design and assessment of reinforced concrete bridge deck slabs, the slab shall be checked under both global and local loading cases. The conventional means of analysing these slabs is by assuming flexural action. In this Standard, criteria are given for the analysis of deck slabs using compressive membrane action.

2.2 At present, it is usual to use the methods of Westergaard(1) or Pucher(2) to derive the local flexural effects of a wheel load, which can be added to the global flexural effects to design and assess bridge deck slabs. This standard provides a less conservative, alternative approach, which allows for compressive membrane action.

2.3 Many of the criteria given in this Standard are based on experimental evidence(3), which has been conservatively interpreted for use in design and assessment.

Compressive membrane action

2.4 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, which can significantly increase the load capacity of the slab, is known as compressive membrane action, as illustrated in Figure 2.1.

Restraint

2.5 Bridge deck slabs require restraint along all four boundaries in order for compressive membrane action to be reliably mobilised. The limitations set out in 5.10 assure that adequate restraint to the deck slab, is available.

Applicability

2.6 The methods given in this standard are primarily intended for use with steel and concrete beam and slab type bridge decks, including those with participating precast concrete formwork, where adequate boundary restraint is available to deck slabs.

2.7 The following are specifically excluded and, as such, shall be designed or assessed in accordance with BD24 or BD44 as appropriate:

i) Cantilever overhangs.

ii) Deck slabs where the Engineer cannot reliably justify that sufficient restraint is available.

Loads to be considered

2.8 Loadings shall be in accordance with the Departmental Standards BD 37 ‘Loads for highway structures’ for design and BD 21 ‘The assessment of highway bridges and structures’ for assessment.

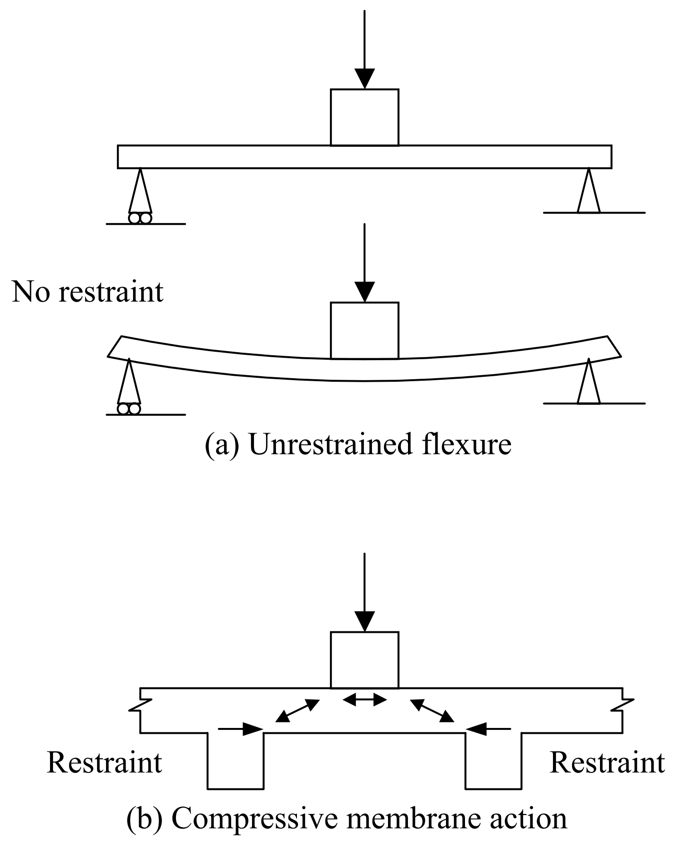

Figure 2.1: Structural Behaviour of Unrestrained and Restrained Slabs

3. DESIGN

General

3.1 Reinforced concrete bridge deck slabs shall be designed in accordance with the relevant parts of BD 24 and this Standard

Analysis for serviceability - Rigorous design

3.2 Non-linear analysis including non-linear finite element analysis may be used with the agreement of Overseeing Organisation. Due to the complexity of such an analysis, non-linear analysis should only be undertaken in circumstances where the Engineer considers it absolutely necessary.

Analysis for serviceability - Simplified design

3.3 In order to allow for the effects of compressive membrane action on the global load distribution, 2 separate analyses shall be carried out using the flexural stiffness constants (second moments of area) for sections of discrete members or unit widths of slab elements as follows:

i) Design of members spanning in the direction of compressive membrane action, (ie the deck slab in beam and slab construction):

   The entire member cross-section, ignoring the reinforcement, for all members.

ii) Design of members spanning in the other direction, (ie 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 (ie the deck slab), and the full member cross-sectional width, ignoring the reinforcement, for the other members (eg longitudinal beams).

Alternatively, to avoid the need to undertake two separate analyses, the deck slab may be designed for twice the moment given by analysis ii) above.

Analysis for ultimate limit state - Rigorous design

3.4 Non-linear methods may be used as stated in 3.2. Where non-linear analysis is used to justify use of membrane action in slabs with span to depth ratios greater than given in 5.10(c), the effect of geometric non-linearity shall be considered. Usually, and whenever non-linear analysis is used to analyse decks which do not comply with 5.10(f), it will be necessary to consider critical global load cases and to analyse a whole span of the bridge.

Analysis for ultimate limit state - Simplified design

3.5 Elastic methods may be used to determine the distribution of forces as stated in 3.3

3.6 The empirical method given in 5.2 to 5.9 may be used for local analysis provided the slabs comply with all the limitations of 5.10. If, in addition to complying with the limitations of 5.10, the slab is at least 160mm thick and of at least grade 40 concrete, the local strength may be assumed adequate for up to 45 units of HB.

Combined global and local effects

3.7 In addition to the design of individual primary and secondary elements to resist loading applied directly to them, it is also necessary to consider the loading which produces the most adverse effects due to combined global and local loading where they co-exist.

3.8 Analysis of the structure may be accomplished by one overall analysis (for instance, non-linear finite element analysis for rigorous design) or by separate analyses for global and local effects.

Combination for serviceability limit state

3.9 For reinforced concrete bridge deck slab panels with adequate boundary restraint, as defined in 5.10, the crack width due to global effects only shall be determined in accordance with BD 24.

3.10 For reinforced concrete bridge deck slab panels without adequate boundary restraint, as defined in 5.10, the total crack width due to combined global and local effects shall be determined in accordance with BD 24.

Combination for ultimate limit state

3.11 For reinforced concrete bridge deck slabs with adequate boundary restraint, as defined in 5.10, the deck slab reinforcement shall be derived, in accordance with BD 24, on the basis of global effects only. The resistance to local effects should be derived from 5.2 to 5.9. Punching shear is taken account of through the procedures presented in this Standard.

3.12 For reinforced concrete bridge deck slabs without adequate boundary restraint, as defined in 5.10, the resistance of the deck slab to combined global and local effects shall be derived from the direct strain due to global effects combined with the flexural strain due to local effects in accordance with BD 24.

Minimum Area of Reinforcement

3.13 The minimum steel area provided in the deck slab in each face in each direction shall be 0.3% of the gross concrete section. The spacing of the bars shall be not greater than 250mm. In addition, the reinforcement in both faces in the direction of the primary slab span shall be not less than 750mm^2/m.

3.14 Where, in for example continuous bridges, longitudinal reinforcement is required in the deck slab to resist global effects, the nominal steel required by 3.13 shall be provided in addition to the steel required to resist global effects. Not less than 30% of the steel required for global effects shall be placed in the bottom face of the slab. The provision of 0.3% additional longitudinal reinforcement in each face for global analysis may be quite onerous, especially as 3.3 will result in the longitudinal members having more reinforcement.

4. ASSESSMENT

General

4.1 Reinforced concrete bridge deck slabs shall be assessed in accordance with the relevant parts of BD 44 and this Standard.

Analysis for Ultimate Limit State – Rigorous Assessment

4.2 Non-linear analysis including non-linear finite element analysis may be used with the agreement of the Overseeing Organisation. Due to the complexity of such an analysis, non-linear finite element analysis should only be undertaken in circumstances where the Engineer considers it absolutely necessary. Where non-linear analysis is used to justify use of membrane action in slabs with span to depth ratios greater than given in 5.10, the effect of geometric non-linearity shall be considered. Usually, and whenever non-linear analysis is used to analyse decks which do not comply with 5.10(f), it will be necessary to consider critical global load cases and to analyse a whole span of the bridge.

Analysis for Ultimate Limit State – Simplified Assessment

4.3 In order to allow for the effects of compressive membrane action on the global load distribution, 2 separate analyses shall be carried out using the flexural stiffness constants (second moments of area) for sections of discrete members or unit widths of slab elements as follows:

i) Assessment of members spanning in the direction of compressive membrane action, (ie the deck slab in beam and slab construction).

   The entire member cross-section, ignoring the reinforcement, for all members.

ii) Assessment of members spanning in the other direction, (ie 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 (ie the deck slab), and the full member cross-sectional width, ignoring the reinforcement, for the other members (eg longitudinal beams).

Alternatively, to avoid the need to undertake two separate analyses, the deck slab may be assessed for twice the moment given by analysis ii) above.

4.4 The empirical method given in 5.2 to 5.9 may be used for local analysis provided the reinforcement complies with the requirements of 3.13 - 3.14. If, in addition to complying with the limitations of 5.10, the slab is at least 160mm thick and of at least grade 40 concrete, the local strength may be assumed adequate for up to 45 units of HB.

Combined Global and Local Effects

4.5 In addition to the assessment of individual primary and secondary elements to resist loading applied directly to them, it is also necessary to consider the loading which produces the most adverse effects due to combined global and local loading where they co-exist.

4.6 Analysis of the structure may be accomplished by one overall analysis (non-linear finite element analysis for the rigorous assessment) or by separate analyses for global and local effects.

Combination for Ultimate Limit State

4.7 For reinforced concrete bridge deck slabs with adequate boundary restraint, as defined in 5.10, all of the member reinforcement shall be used to derive the global resistance, as described in BD 44. The resistance to local effects should be derived from 5.2 to 5.9. Punching shear is taken account of through the procedures presented in this Standard.

4.8 For reinforced concrete bridge deck slabs without adequate boundary restraint, as defined in 5.10, the resistance of the deck slab to combined global and local effects shall be derived from the direct strain due to global effects combined with the flexural strain due to local effects as described in BD 44.

Additional Requirements for Assessment

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

5. SIMPLIFIED METHOD FOR CALCULATING THE LOCAL CAPACITY OF BRIDGE DECK SLABS

General

5.1 The following is a simplified method[3] for calculating the ultimate local capacity of laterally restrained deck slabs. It assumes that the slab reinforcement makes no contribution to the local load carrying capacity.

Procedure

5.2 The following notation applies to 5.2 to 5.10

d average effective depth to the tensile reinforcement (mm)

f_{cu} characteristic concrete cube strength (N/mm^2)

h overall slab depth (mm) (for precast concrete participating formwork panels, to allow for the reduced depth at panel joints, h shall be taken as the overall depth minus 10 mm)

L_r half span of slab strip with boundary restraint (as defined in 1.8) (mm)

γ_M = partial safety factor for strength

φ = diameter of loaded area (mm)

5.3 The concrete compressive cube strength shall be expressed as an equivalent cylinder strength, f_c(N/mm^2). This is given by.

$$f_c = \frac{0.8 f_{cu}}{\gamma_m} \qquad \text{Equation 1}$$

5.4 The plastic strain[4] of an idealised elastic-plastic concrete, ε_c , is given by.

$$\varepsilon_c = (-400 + 60 f_c - 0.33 f_c^2) \text{ x } 10^{-6} \qquad \text{Equation 2}$$

5.5 The non-dimensional parameter for arching moment of resistance, R, is given by.

$$R = \frac{\varepsilon_c L_r^{\,2}}{h^2} \qquad \text{Equation 3}$$

In order for the deck slab to be treated as restrained R must be less than 0.26. If this condition is not met the deck slab shall be treated as if it were unrestrained and benefit from compressive membrane action to enhance the load capacity of the slab, cannot be assumed.

5.6 The non-dimensional arching moment co-efficient, k, is given by.

$$k = 0.0525\ (4.3 - 16.1\sqrt{3.3x10^{-4} + 0.1243R}) \qquad \text{Equation 4}$$

5.7 The effective reinforcement ratio, ρ_e, is given by.

$$\rho_e = k\left[\frac{f_c}{240}\right]\left[\frac{h}{d}\right]^2 \qquad \text{Equation 5}$$

5.8 The ultimate predicted load for a single wheel, P_{ps}(N), is given by.

$$P_{ps} = 1.52(\varphi + d)d\sqrt{f_c}\,(100\rho_e)^{0.25} \qquad \text{Equation 6}$$

5.9 Until further research is available, 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.

$$P_{pd} = 0.65P_{ps} \qquad \text{Equation 7}$$

Limitation

5.10 Until further research is available on the use of the procedures given in 5.2 to 5.9, the procedures shall only be used on bridge deck slabs which comply with the following limitations:

(a) The transverse (primary) span length of a slab panel perpendicular to the direction of traffic should not exceed 3.7 m.

(b) The slab shall extend at least 1.0m beyond the centre line of the external longitudinal supports of a panel. In the case of an external panel, a kerb or string course integral with the slab may be used instead of the 1.0m overhang, provided that the combined cross-sectional area of slab and curb, beyond the centre line of the external girder, is not less than the cross-sectional area of one metre length of deck slab.

(c) The span length to thickness ratio of the slab should not exceed 15; in skew slabs, the skew span shall be used in calculating this ratio.

(d) For skew angles greater than 20^o, the end portions of the deck slab shall be designed or assessed in accordance with BD 24 or BD 44 as appropriate.

(e) Transverse edges at the ends of the bridge and at intermediate points where the continuity of the slab is broken shall be supported by diaphragms or other suitable means and shall be designed for the full effects of the wheel loads.

(f) Cross frames or diaphragms shall be provided at the support lines of all bridges. Bridges with steel beams will also have cross frames or diaphragms at centres not exceeding 8m or half the span of the bridge. Bridges with concrete beams other than prestressed beams complying with the serviceability limitations of BD 24, shall have at least one intermediate diaphragm in each span. All the cross frames or diaphragms will extend throughout the width of the bridge between external girders and will extend from the top to the bottom flange, or in the case of T section beams with no distinct bottom flange, from the slab over at least 75% of the depth of the web.

(g) Edge beams shall be provided for all slabs having main reinforcement parallel to traffic. An edge beam may 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 wall to stiffen the edge of the slab.

6. REFERENCES

6.1 The following Departmental and British Standards Institution documents are referred to in this standard:

Departmental Standard BD 24/92: Design of Concrete Bridges. Use of BS 5400: Part 4: 1990.

Departmental Standard BD 44/95: The Assessment of Concrete Highway Bridges and Structures.

Departmental Standard BD 37/88: Loads for Highway Bridges.

Departmental Standard BD 21/97: The Assessment of Concrete Highway Bridges and Structures.

British Standard BS 6100: Glossary of Building and Civil Engineering Terms

6.2 The following references provide background information to the provisions of this standard:

(1) Westergaard, H.M. 'Computation of stresses in bridge slabs due to wheel loads' Public Roads, 11, No. 1, March 1930 pp1-23

(2) Pucher, A. 'Influence surfaces of elastic plates' Wien, New York, Springer Verlag, 1964, pp33, ch. 93

(3) Kirkpatrick, J., Rankin, G.I.B. and Long, A.E. 'Strength evaluation of M-beam bridge deck slabs' The Structural Engineer Vol. 62B No.3 Sept 1984 pp60-8

(4) Hognestad, E., Hanson, N.W. and McHenry, D. 'Concrete stress distribution in ultimate strength design' Journal of the American Institute Proceedings 52, No. 6 December 1955 pp455-479

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