

Steel, concrete and composite bridges —

Part 5: Code of practice for design of composite bridges

UDC 624.21.01:624.016

NO COPYING WITHOUT BSI PERMISSION EXCEPT AS PERMITTED BY COPYRIGHT LAW



Document Sharing Hub

Cooperating organizations

The Civil Engineering and Building Structures Standards Committee, under whose direction this British Standard was prepared, consists of representatives from the following Government departments and scientific and industrial organizations:

- Aluminium Federation
- Association of Consulting Engineers*
- Brick Development Association
- British Precast Concrete Federation Ltd.*
- British Steel Corporation
- British Steel Industry*
- Cement and Concrete Association*
- Concrete Society Limited*
- Consumers Standards Advisory Committee of BSI
- Convention of Scottish Local Authorities
- County Surveyor's Society
- Department of the Environment (Building Research Establishment)*
- Department of the Environment (Housing and Construction)
- Department of the Environment (Transport and Road Research Laboratory)*
- Department of the Environment (PSA)
- Department of the Environment (Water Engineering Division including Water Data Unit)
- Department of Transport*
- Health and Safety Executive

The organizations marked with an asterisk in the above list, together with the following, were directly represented on the committee entrusted with the preparation of this British Standard:

- Association of County Councils
- British Constructional Steelwork Association
- British Railways Board
- Constructional Steel Research and Development Organisation
- Greater London Council
- Federation of Civil Engineering Contractors
- Institution of Highway Engineers
- Ministry of Defence
- Sand and Gravel Association Limited
- Welding Institute
- Institution of Civil Engineers*
- Institution of Municipal Engineers*
- Institution of Public Health Engineers
- Institution of Structural Engineers*
- Institution of Water Engineers and Scientists
- London Transport Executive*
- Ministry of Agriculture Fisheries and Food
- National Water Council
- Royal Institute of British Architects
- Scottish Development Department*
- Trades Union Congress

This British Standard, having been prepared under the direction of the Civil Engineering and Building Structures Standards Committee, was published under the authority of the Executive Board on 30 April 1979

© BSI 10-1999

The following BSI references relate to the work on this Standard:
Committee reference CSB/30
Draft for comment 75/10554

ISBN 0 580 10347 1

Amendments issued since publication

Amd. No.	Date of issue	Comments
3998	May 1982	Indicated by a sideline in the margin

Contents

	Page
Cooperating organizations	Inside front cover
Foreword	2
1 Scope	1
2 References	1
3 Definitions and symbols	1
3.1 Definitions	1
3.2 Symbols	2
4 Design: general	3
4.1 Design philosophy	3
4.1.1 General	3
4.1.2 Design loads due to shrinkage of concrete	3
4.1.3 Design loading effects	3
4.2 Material properties	4
4.2.1 General	4
4.2.2 Structural steel	4
4.2.3 Concrete, reinforcement and prestressing steels	4
4.3 Limit state requirements	4
4.3.1 General	4
4.3.2 Serviceability limit state	4
4.3.3 Ultimate limit state	4
5 Design and detailing of superstructure for the serviceability limit state	4
5.1 Analysis of structure	4
5.1.1 Distribution of bending moments and vertical shear forces	4
5.2 Analysis of sections	5
5.2.1 General	5
5.2.2 Analysis	5
5.2.3 Effective breadth of concrete flange	5
5.2.4 Deck slabs forming flanges of composite beams	7
5.2.5 Steel section	7
5.2.6 Control of cracking in concrete	7
5.3 Longitudinal shear	8
5.3.1 General	8
5.3.2 Shear connectors	9
5.3.3 Design of shear connection	14
5.4 Temperature effects and shrinkage modified by creep	15
5.4.1 General	15
5.4.2 Temperature effects	15
5.4.3 Shrinkage modified by creep	16
5.5 Deflections	16
5.5.1 General	16
5.5.2 Calculation of deflections	16
6 Design and detailing of superstructure for the ultimate limit state	17
6.1 Analysis of structure	17
6.1.1 General	17
6.1.2 Deck slabs forming the flanges of composite beams	17
6.1.3 Composite action	17
6.1.4 Distribution of bending moments and vertical shear forces	17

		Page
6.1.5	Temperature effects and shrinkage modified by creep	18
6.2	Analysis of sections	18
6.2.1	General	18
6.2.2	Definitions	18
6.2.3	Analysis of compact cross sections	18
6.2.4	Analysis of slender cross sections	19
6.3	Longitudinal shear	20
6.3.1	General	20
6.3.2	Deck slab	20
6.3.3	Transverse reinforcement	20
6.3.4	Shear connectors	23
7	Composite box girders	23
7.1	General	23
7.2	Effective span	23
7.3	Effective breadth	23
7.4	Distribution of bending moments and vertical shear forces	23
7.5	Longitudinal shear	23
7.5.1	Spacing of shear connectors	23
7.5.2	Design of shear connectors	24
7.6	Torsion	24
7.7	Composite plate	24
8	Cased beams and filler beam construction	25
8.1	Scope	25
8.2	Limit state requirements	25
8.3	Analysis of structure	25
8.3.1	Transverse moments in filler beam decks (approximate method)	25
8.4	Analysis of sections	25
8.4.1	Serviceability limit state	25
8.4.2	Ultimate limit state	25
8.5	Longitudinal shear	25
8.5.1	Serviceability limit state	25
8.5.2	Ultimate limit state	26
8.6	Temperature and shrinkage effects	26
8.6.1	General	26
8.6.2	Longitudinal stresses and strains	26
8.6.3	Longitudinal shear	26
8.7	Control of cracking	26
8.7.1	General	26
8.7.2	Cased beams	26
8.7.3	Filler beams	27
8.8	Design and construction	27
9	Permanent formwork	27
9.1	General	27
9.2	Materials	27
9.3	Structural participation	27
9.4	Temporary construction loading	27
9.5	Design	27
9.5.1	General	27

	Page
9.5.2 Non-participating formwork	27
9.5.3 Participating formwork	27
9.6 Precast concrete or composite precast concrete permanent formwork	27
9.6.1 Design	27
9.6.2 Welding of reinforcement	28
9.6.3 Interfaces	28
9.6.4 Cover to reinforcement	28
10 The use of friction grip bolts as shear connectors in composite beams	28
10.1 General	28
10.2 Design requirements: static loading	28
10.2.1 Serviceability limit state	28
10.2.2 Ultimate limit state	28
10.3 Fatigue	28
10.4 Other considerations	28
11 Composite columns	28
11.1 General	28
11.1.1 Scope	28
11.1.2 Materials	29
11.1.3 Shear connection	29
11.1.4 Concrete contribution factor	29
11.1.5 Limits on slenderness	29
11.2 Moments and forces in columns	30
11.2.1 General	30
11.2.2 Semi-empirical design method for restrained composite columns	30
11.3 Analysis of column cross section	30
11.3.1 General	30
11.3.2 Axially loaded columns	31
11.3.3 Columns under uniaxial bending about the minor axis	31
11.3.4 Columns under uniaxial bending about the major axis restrained from failure about the minor axis	31
11.3.5 Columns under uniaxial bending about the major axis unrestrained against failure about the minor axis	32
11.3.6 Columns under biaxial bending	32
11.3.7 Ultimate strength of axially loaded concrete filled circular hollow sections	32
11.3.8 Tensile cracking of concrete	32
11.3.9 Design details	33
12 Influence of method of construction on design	33
12.1 Sequence of construction	33
12.2 Permanent formwork	33
13 Prestressing in composite construction	33
13.1 General	33
13.2 Methods of prestressing	33
13.3 Limit state requirements	33
13.4 Prestressing the steel beam	33
13.5 Stress limitations in concrete at transfer	34
13.6 Loss of prestress	34

	Page
Appendix A Calculation of effective breadth ratios Ψ	34
A.1 General	35
A.2 Equivalent simply supported spans	35
A.3 Point loads not at midspan	35
A.4 Combination of loads	35
Appendix B Calculation of crack widths in composite members	35
B.1 General	35
B.2 Formula for estimating crack widths due to flexure	36
Appendix C Formulae and tables for the design of composite columns	36
C.1 Coefficient K_1	36
C.2 Coefficient K_2	41
C.3 Coefficient K_3	41
C.4 Ultimate moment of resistance M_u of composite columns	41
Figure 1 — Distribution of longitudinal stress in the concrete flange of a composite beam	8
Figure 2 — Shear connectors	11
Figure 3 — Dimensions of haunches	13
Figure 4 — Dimensions of specimens for test on shear connectors	13
Figure 5 — Range of concrete mixes for which Table 9 can be used	17
Figure 6 — Shear planes and transverse reinforcement	21
Figure 7 — Coefficient K	24
Figure 8 — Force diagrams for calculating M_u	44
Figure 9 — Chart for evaluating M_u of concrete filled circular hollow sections	27
Table 1 — Values of the partial safety factor for materials γ_m	4
Table 2 — Effective breadth ratios Ψ for simply supported beams	5
Table 3 — Effective breadth ratios Ψ for cantilever beams	6
Table 4 — Effective breadth ratios Ψ for internal spans of continuous beams	6
Table 5 — Clear distance (mm) between bars in tension for propped construction	9
Table 6 — Clear distance (mm) between bars in tension for unpropped construction	9
Table 7 — Nominal static strengths of shear connectors for different concrete strengths	10
Table 8 — Properties of concrete flange for calculation of temperature effects	15
Table 9 — Shrinkage strains and creep reduction factors	16
Table 10 — Maximum percentage redistribution of bending moments at the ultimate limit state	18
Table 11 — Effective length of columns	30
Table 12 — Values of constants C_1 and C_2 for axially loaded concrete filled circular hollow sections	32
Table 13 — Strut curve selection chart	37
Table 13.1 — Values of coefficient K_1 for column curve a	38
Table 13.2 — Values of coefficient K_1 for column curve b	39
Table 13.3 — Values of coefficient K_1 for column curve c	40
Table 14 — Values of Ψ coefficient	40
Publications referred to	Inside back cover

Foreword

BS 5400 is a document combining codes of practice to cover the design and construction of steel, concrete and composite bridges and specifications for loads, materials and workmanship.

It comprises the following Parts:

- *Part 1: General statement;*
- *Part 2: Specification for loads;*
- *Part 3: Code of practice for design of steel bridges¹⁾;*
- *Part 4: Code of practice for design of concrete bridges;*
- *Part 5: Code of practice for design of composite bridges;*
- *Part 6: Specification for materials and workmanship, steel;*
- *Part 7: Specification for materials and workmanship, concrete, reinforcement and prestressing tendons;*
- *Part 8: Recommendations for materials and workmanship, concrete, reinforcement and prestressing tendons;*
- *Part 9: Code of practice for bearings¹⁾;*
- *Part 10: Code of practice for fatigue.*

In the drafting of BS 5400 important changes have been made in respect of loading and environmental assumptions, design philosophy, load factors, service stresses and structural analysis. Furthermore, recourse has been made to recent theoretical and experimental research and several design studies have been made on components and on complete bridges. It is to be expected that as design experience of different bridge types is accumulated, further modifications will be required.

It should be noted that this Part of BS 5400 supersedes CP 117-2.

The relationship between Part 3 and Part 5. The design of composite bridges requires the combined use of Part 5 and Part 3 of BS 5400.

Part 5 was published in 1979, the major decision on scope and approach having been taken some years previously; Part 3 was published in 1982. It is natural therefore that some differences will exist between Part 3 and Part 5.

Part 3 has been drafted on the assumption that for the design of steelwork in bridges with either steel or concrete decks the methods of global analysis and all the procedures for satisfying the limit state criteria will be as prescribed in Part 3. For beams Part 3 may be used without any modification in conjunction with those provisions of Part 5 that are applicable to the properties of the composite slab and its connection to the steel section.

Part 5 also contains optional provisions for increased redistribution of longitudinal moments in compact members or for plastic analysis of continuous beams for the ultimate limit state, which could prove economical in some instances. These procedures require special consideration of increased transverse deformations of the slab, which is not covered in Part 5, and of stability of the bottom flange, which is not covered in Part 3: they should not be used unless proper account is taken of these considerations.

It will be noted that more serviceability checks are required for composite than for steel bridges. This difference is due to the special characteristics of composite construction, such as the large shape factor of certain composite sections; the addition of stresses in a two-phase structure (bare steel/wet concrete and composite); and the effects of shrinkage and temperature on the girders and on the shear connectors.

¹⁾ In course of preparation.

The method given in 4.1.3 a) of part 5 should not be used, when the relationship between loading and load effects is non linear, and the values of γ_m for structural steel given in Table 1 of Part 5 should not be used and reference made to Table 2 of Part 3.

It is intended to revise Parts 3 and 5 to coordinate them fully after there has been sufficient experience of their application.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to vi, pages 1 to 46, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

1 Scope

This Part of this British Standard supersedes CP 117-2 and augments the provisions of BS 5400-3, BS 5400-4 and BS 5400-10 for structural steel and reinforced or prestressed concrete when components of these materials are so interconnected that they act compositely.

It gives recommendations for rolled or fabricated steel sections, cased or uncased, and for filler beam systems. Consideration is given to simply supported and continuous composite beams, composite columns and to the special problems of composite box beams. The recommendations for the concrete element cover normal and lightweight aggregate, cast in situ and precast concrete. Prestressing and the use of permanent formwork designed to act compositely with in situ concrete are also covered.

2 References

The titles of the publications referred to in this Part of BS 5400 are listed in the inside back cover.

3 Definitions and symbols

3.1 Definitions

For the purposes of this Part of this British Standard the following definitions, and those given in Part 1, apply.

3.1.1

cased composite beam

a beam composed of either rolled or built-up structural steel sections, with a concrete encasement, which acts in conjunction with a concrete slab where the two elements are interconnected so as to form a composite section

3.1.2

uncased composite beam

a beam composed of either rolled or built-up structural steel sections, without a concrete encasement, which acts in conjunction with a concrete slab where the two elements are interconnected so as to form a composite section

3.1.3

composite box beam

a steel box girder acting compositely with a concrete slab

NOTE In a closed steel box the concrete is cast on the top steel flange whereas in an open steel box the box is closed by the concrete slab.

3.1.4

composite column

a column composed either of a hollow steel section with an infill of concrete or of a steel section cased in concrete so that in either case there is interaction between steel and concrete

3.1.5

composite plate

an in situ concrete slab cast upon, and acting compositely with, a structural steel plate

3.1.6

concrete slab

the structural concrete slab that forms part of the deck of the bridge and acts compositely with the steel beams. The slab may be of precast, cast in situ or composite construction

3.1.7

composite slab

an in situ concrete slab that acts compositely with structurally participating permanent formwork

3.1.8

participating permanent formwork

formwork to in situ concrete, when the strength of the formwork is assumed to contribute to the strength of the composite slab

3.1.9

non-participating permanent formwork

permanent formwork that may or may not act compositely with the in situ concrete but where the formwork is neglected in calculating the strength of the slab

3.1.10

filler beam construction

rolled or built-up steel sections that act in conjunction with a concrete slab and which are contained within the slab

3.1.11 Interaction

3.1.11.1

complete interaction

this implies that no slip occurs between the steel and the concrete slab or encasement

3.1.11.2

partial interaction

this implies that slip occurs at the interface between steel and concrete and a discontinuity in strain occurs

3.1.12

shear connector

a mechanical device to ensure interaction between concrete and steel

3.1.13 connector modulus

the elastic shear stiffness of a shear connector

3.2 symbols

The symbols used in this Part of this standard have been derived in accordance with Appendix F of CP 110-1:1972 and are as follows.

A_b	Cross-sectional area of transverse reinforcement in the bottom of the slab	E_c	Static secant modulus of elasticity of concrete
A_{bs}	Cross-sectional area of other transverse reinforcement in the bottom of the slab	E_r	Modulus of elasticity of steel reinforcement
A_{bv}	Cross-sectional area of additional transverse reinforcement	E_s	Modulus of elasticity of structural steel
A_c	Cross-sectional area of concrete	F_T	Tensile force per unit length
A_e	Effective cross-sectional area of transverse reinforcement	f_c	Concrete strength
A_f	Cross-sectional area of top flange of steel section	f_{cc}	Enhanced characteristic strength of triaxially contained concrete
A_r	Cross-sectional area of reinforcement	f_{ci}	Concrete strength at (initial) transfer
A_s	Cross-sectional area of the steel section	f_{cu}	Characteristic concrete cube strength
A_{st}	Area of the encased tension flange of the structural steel member	f_L	Longitudinal stress
A_t	Area of tension reinforcement, cross-sectional area of transverse reinforcement near the top of the slab	f_{max}	Maximum longitudinal stress in concrete flange
α'	Distance from the compression face to the point at which the crack width is calculated	f_{ry}	Characteristic strength of reinforcement
α_{cr}	Distance from the point considered to the surface of the nearest longitudinal bar	f_{tc}	Tensile stress in uncracked concrete flange
b	Width of section or portion of flange or least lateral dimension of a column	f_y	Reduced nominal yield strength of the steel casing
b_e	Effective breadth of portion of flange	f_y	Nominal yield strength of structural steel
b_f	Breadth of flange	h	Thickness (with appropriate subscripts), greatest lateral dimension of a column
b_s	External dimension of the wall of the RHS	h_c	Thickness of the concrete slab forming the flange of the concrete beam
b_t	Effective breadth of the composite section at the level of the tension reinforcement	I	Second moment of area (with appropriate subscripts)
b_w	Half the distance between the centre lines of webs	K	A constant (with appropriate subscripts)
C	A constant (with appropriate subscripts)	k	A constant (with appropriate subscripts)
c_{min}	Minimum cover to the tension reinforcement	L_s	Length of the shear plane under consideration
D	Diameter	l	Distance from face of support to the end of a cantilever, or effective span of a beam (distance between centres of supports) or length of column between centres of end restraints ^a
D_e	External diameter	l_E	Length of column for which the Euler load equals the squash load
d_c	Depth to neutral axis in composite column	l_e	Effective length of a column or l_x or l_y as appropriate
d_r	Separation of symmetrically placed reinforcing bars	l_S	Distance from end of beam
d_s	Thickness of the concrete cover of encased steel section	l_{ss}	One-fifth of the effective span
d_w	Depth of steel web in compression zone	M	Bending moment (with appropriate subscripts)
		M_{max}	Maximum moment
		M_u	Ultimate moment of resistance
		M_{ux}	Ultimate moment of resistance about the major axis
		M_{uy}	Ultimate moment of resistance about the minor axis
		M_x	Moment acting about the major axis, longitudinal bending moment per unit width of filler beam deck

M_y	Moment acting about the minor axis, longitudinal bending moment per unit width of filler beam deck	γ_{fL}	Partial safety factor for loads and load effects
m	Constant	$\gamma_{f1}, \gamma_{f2}, \gamma_{f3}$	Partial safety factors for loads and load effects
N	Ultimate axial load at the section considered	γ_m	Partial safety factor for strength
N_{ax}, N_{ay}	Axial failure loads	Δf	Difference between the free strains at the centroid of the concrete slab and the centroid of the steel beam
N_u	Squash load of a column	ϵ_{cs}	Free shrinkage strain
N_x	Design failure load of a column subjected to a constant design moment M_x	ϵ_m	Average strain
N_{xy}	Strength of a column in biaxial bending	ϵ_1	Strain at the level considered
N_y	Design failure load of a column subjected to a constant design moment M_y	η	Imperfection constant for composite columns
n	Total number of connectors per unit length of girder	λ	Slenderness function (with appropriate subscripts)
n'	Number of connectors per unit length placed within 200 mm of the centre line of the web	λ_E	Euler slenderness function
P_u	Nominal static strength	μ	Coefficient of friction
P	Failure load of the connectors at concrete strength f_c	ρ	Ratio of the average compressive stress in the concrete at failure to the design yield strength of steel, taken as $0.4 f_{cu}/0.91 f_y$
Q	Longitudinal shear force	Φ	Bar size
Q^*	Design load	ϕ	Creep coefficient
q	Longitudinal shear per unit length	ϕ_c	Creep reduction factor
q_p	Design longitudinal shear force per unit length of beam on the particular shear plane considered	χ	Non-dimensional coordinate
S	Plastic section modulus	Ψ	Effective breadth ratio, coefficient
S^*	Design loading effects	^a In Appendix A l is used as the distance between adjacent points at which the bending moment is zero.	
s	A constant stress of 1 N/mm^2 re-expressed where necessary in units consistent with those used for other quantities		
s_b	Spacing of bars		
T_u	Tension		
t	Wall thickness		
t_f	Flange thickness		
t_w	Web thickness		
x	Neutral axis depth, coordinate		
y	Coordinate		
α_c	Concrete contribution factor		
α_e	Modular ratio		
α_L	Ratio of the product of the partial safety factors $\gamma_{fL} \gamma_{f3}$ for HB loading to the corresponding product for HA loading for the limit state being considered		
β	Ratio of the smaller to the larger of the two end moments acting about each axis with appropriate subscripts		
β_L	Coefficient of linear thermal expansion		

4 Design: general

4.1 Design philosophy

4.1.1 General. Design should be in accordance with Part 1.

4.1.2 Design loads due to shrinkage of concrete. For shrinkage modified by creep the partial safety factor γ_{fL} should be taken as 1.0 for the serviceability limit state and 1.2 for the ultimate limit state.

NOTE For the definition of the partial safety factor, see Part 1.

4.1.3 Design loading effects. The design loading effects S^* for design in accordance with this Part of this British Standard may be determined from the design loads Q^* from either:

- $S^* = \text{effects of } (\gamma_{f3} Q^*) \text{ or}$
- $S^* = \gamma_{f3} (\text{effects of } Q^*)$.

The partial factor of safety γ_{f3} should be taken as 1.10 at the ultimate limit state and 1.0 at the serviceability limit state.

Where the relationship between loading and load effects is non-linear, as for example in slender columns or in beams designed using simple plastic theory, the method given in a) is the more simple.

4.2 Material properties

4.2.1 General. In analysing a structure to determine the load effects, the material properties associated with the unfactored characteristic strength should be used irrespective of the limit state being considered. For analysis of sections, the appropriate value of the partial factor of safety γ_m , to be used in determining the design strength, should be taken from Part 3 or Part 4 depending on the materials and the limit state. Except where specifically stated, it may be assumed that allowance has been made in the limiting stresses and expressions given in this Part of this British Standard, for the values of γ_m given in Table 1.

Table 1 — Values of the partial safety factor for materials γ_m

Material	Serviceability limit state	Ultimate limit state
Structural steel	1.0	1.10
Reinforcement	1.0	1.15
Concrete	1.0 or 1.3 (as appropriate)	1.5
Shear connectors	1.0	1.10

4.2.2 Structural steel. The characteristic or nominal properties of structural steel should be determined in accordance with Part 3.

4.2.3 Concrete, reinforcement and prestressing steels. The characteristic properties of concrete, reinforcement and prestressing steels should be determined in accordance with Part 4. For sustained loading, it should be sufficiently accurate to assume a modulus of elasticity of concrete equal to one half of the value used for short term loading.

4.3 Limit state requirements

4.3.1 General. Except where otherwise recommended in this Part of this British Standard the design of structural steelwork and structural concrete elements forming part of a composite structure should satisfy the recommendations of Parts 3, 4 and 10.

4.3.2 Serviceability limit state. A serviceability limit state is reached when any of the following conditions occur:

- the stress in structural steel reaches the appropriate limit given in Part 3;
- the stress in concrete, reinforcement or prestressing tendons reaches the appropriate limit given in Part 4;
- the width of a crack in concrete, calculated in accordance with 5.2.6, reaches the appropriate limit given in Part 4;

d) the slip at the interface between steel and concrete becomes excessive.

NOTE This is assumed to occur when the calculated load on a shear connector exceeds 0.55 times its nominal static strength;

e) the vibration in a structure supporting a footway or cycle track reaches the appropriate limit given in Part 2.

4.3.3 Ultimate limit state. General recommendations for composite structures at the ultimate limit state are as given in Part 1.

5 Design and detailing of the superstructure for the serviceability limit state

5.1 Analysis of structure

5.1.1 Distribution of bending moments and vertical shear forces

5.1.1.1 General. The distributions of bending moments and vertical shear forces, due to loading on the composite member, may be calculated by an elastic analysis assuming the concrete to be uncracked and unreinforced. The effects of shear lag may be neglected.

5.1.1.2 Continuous beams. In continuous beams, at each internal support, the apparent tensile stress in the concrete at the top surface of the slab due to the maximum design hogging (negative) moment obtained from 5.1.1.1 should be calculated. For this calculation, the composite section should be taken as the appropriate steel member acting compositely with a concrete flange equal in breadth to the effective breadth determined in accordance with 5.2.3. The concrete should be assumed to be uncracked and unreinforced. If this tensile stress f_{tc} exceeds $0.1 f_{cu}$ then either:

- a new distribution of bending moments should be determined as in 5.1.1.1 but neglecting the stiffening effect of the concrete over 15 % of the length of the span on each side of each support so affected. For this purpose, longitudinal tensile reinforcement in the slab may be included. Or, alternatively,
- provided adjacent spans do not differ appreciably in length, the maximum design sagging moments in each span adjacent to each support so affected should be increased by $40 f_{tc}/f_{cu}$ % to allow for cracking of the concrete slab at the support. In this case, no reduction should be made in the support moment.

5.1.1.3 Prestressing in continuous beams. Where the concrete flange in the hogging (negative) moment region of a continuous composite beam is longitudinally prestressed the distribution of bending moments and vertical shear forces should be determined in accordance with 5.1.1.1.

5.2 Analysis of sections

5.2.1 General. Composite elements should generally be designed to satisfy the requirements of the serviceability limit state given in 4.3.2 in accordance with 5.1 and 5.2. However, for slender cross sections (see 6.2.2.2) where both the distribution of bending moments and the stresses in the composite section are determined by elastic analysis at the ultimate limit state, temperature and shrinkage effects being included, no check need be made on the flexural stresses at the serviceability limit state, provided the stress limitations at the ultimate limit state given in 6.2.4.1 a) are not exceeded.

5.2.2 Analysis. Stresses due to bending moments and vertical shear forces may be calculated by elastic theory using the appropriate elastic properties given in 4.2 and effective breadths as given in 5.2.3, assuming that there is full interaction between the steel beam and the concrete in compression. Vertical shear should be assumed to be resisted by the steel section alone and the tensile strength of concrete should be neglected.

5.2.3 Effective breadth of concrete flange

5.2.3.1 General. Except as provided in 5.3.1, for longitudinal shear, and 5.5.2, for deflections, and in the absence of a rigorous analysis, allowance for in-plane shear flexibility in the flange (shear lag effects) should be made by using an effective breadth of flange.

NOTE The total effective breadth of flange associated with each web should be taken as the sum of the effective breadths of the portions of flange considered separately on each side of that web. The effective breadth b_e of each portion should be taken as:

a) ψb for portions between webs

where

b is equal to half the distance between the centre lines of webs, measured at the mid-plane of the concrete flange; and

b) $0.85 \psi b$ for portions projecting beyond an outer web

where

b is equal to the distance from the free edge of the projecting portion to the centre line of the outer web, measured at the mid-plane of the concrete flange l is the distance from face of support to the end of a cantilever or the distance between the centres of supports of a beam (except as noted in 5.2.5.4) ψ is the effective breadth ratio from Table 2, Table 3 or Table 4. Values of ψ at cross sections and for ratios b/l other than those covered by Table 2, Table 3 or Table 4 may be obtained by linear interpolation.

Table 2 — Effective breadth ratios ψ for simply supported beams

b/l	Loading uniformly distributed over a length not less than $0.5 l$			Point loading at midspan ^a		
	Midspan	Quarter span	Support	Midspan	Quarter span	Support
0	1.0	1.0	1.0	1.0	1.0	1.0
0.02	0.99	0.99	0.93	0.91	1.0	1.0
0.05	0.98	0.98	0.84	0.80	1.0	1.0
0.10	0.95	0.93	0.70	0.67	1.0	1.0
0.20	0.81	0.77	0.52	0.49	0.98	1.0
0.30	0.65	0.60	0.40	0.38	0.82	0.85
0.40	0.50	0.46	0.32	0.30	0.63	0.70
0.50	0.38	0.36	0.27	0.24	0.47	0.54

^a To be used only for point loads or reactions of significant magnitude not for wheel loads or axle loads.

Table 3 — Effective breadth ratios ψ for cantilever beams

b/l	Loading uniformly distributed over a length not less than $0.5 l$			Point loading at free end ^a		
	Support	Quarter point near support	Free end	Support	Quarter point near support	Free end
0	1.0	1.0	1.0	1.0	1.0	1.0
0.05	0.82	1.0	0.92	0.91	1.0	1.0
0.10	0.68	1.0	0.84	0.80	1.0	1.0
0.20	0.52	1.0	0.70	0.67	0.84	1.0
0.40	0.35	0.88	0.52	0.49	0.74	1.0
0.60	0.27	0.64	0.40	0.38	0.60	0.85
0.80	0.21	0.49	0.32	0.30	0.47	0.70
1.00	0.18	0.38	0.27	0.24	0.36	0.54

^a To be used only for point loads or reactions of significant magnitude not for wheel loads or axle loads.

Table 4 — Effective breadth ratios ψ for internal spans of continuous beams

b/l	Loading uniformly distributed over a length not less than $0.5 l$			Point loading at midspan ^a		
	Midspan	Quarter span	Internal support	Midspan	Quarter span	Internal support
0	1.0	1.0	1.0	1.0	1.0	1.0
0.02	0.99	0.94	0.77	0.84	1.0	0.84
0.05	0.96	0.85	0.58	0.67	1.0	0.67
0.10	0.86	0.68	0.41	0.49	1.0	0.49
0.20	0.58	0.42	0.24	0.30	0.70	0.30
0.30	0.38	0.30	0.15	0.19	0.42	0.19
0.40	0.24	0.21	0.12	0.14	0.28	0.14
0.50	0.20	0.16	0.11	0.12	0.20	0.12

^a To be used only for point loads or reactions of significant magnitude not for wheel loads or axle loads.

5.2.3.2 Standard highway or railway loading. The effective breadth ratios ψ to be used in stress calculations on structural elements subjected to standard highway or railway loading, as specified in Part 2, should be the appropriate values for uniformly distributed loading given in Table 2, Table 3 or Table 4.

5.2.3.3 Width over which slab reinforcement is effective. Only reinforcement placed parallel to the span of the steel beam within the effective breadth of the concrete slab should be assumed to be effective in analysing cross sections.

5.2.3.4 Longitudinal stiffening. The effective breadth ratios given in Table 2, Table 3 and Table 4 take no account of the increase in shear lag in the flange of a composite beam due to the presence of longitudinal stiffening members. Table 2, Table 3 and Table 4 may be taken to apply where the cross-sectional area of longitudinal stiffening members within breadth b does not exceed one quarter of the cross-sectional area of the flange within breadth b and where these areas are calculated for steel and concrete on the basis of the modular ratio. Effective breadth ratios for heavily stiffened steel flanges are given in Part 3.

5.2.3.5 End spans of continuous beams. For end spans of a continuous beam, the effective breadth ratios ψ , for the portion between the end support and the adjacent point of contraflexure, may be calculated in accordance with 5.2.3.1 for simply supported spans by considering the end span as an equivalent span of length $0.9 l$.

5.2.3.6 Transverse members. The effective breadths given in Table 2, Table 3 and Table 4 take no account of any contribution to the in-plane shear stiffness of a flange that may be made by transverse members connected to it.

5.2.3.7 Effective breadth at internal supports. The effective breadth ratio at an internal support may be taken as the mean value of ψ obtained at that support for each span adjacent to that support. For a concrete flange in tension that is assumed to be cracked the mean effective breadth ratio ψ obtained from Table 3 or Table 4 as appropriate, may be modified by adding $(1 - \psi)/3$.

5.2.3.8 Indeterminate structures and special loadings. For indeterminate structures not specifically covered by 5.2.3.1 to 5.2.3.7 and for load positions other than those given in Table 2, Table 3 or Table 4, the effective breadth ratios ψ may be determined by the method given in Appendix A.

5.2.4 Deck slabs forming flanges of composite beams

5.2.4.1 Effects to be considered. The slab should be designed to resist:

- a) the effects of loading acting directly on it, and
- b) the effects of loading acting on the composite member or members of which it forms a part.

These effects should be considered separately and, where they arise together, in conjunction.

Coexistent stresses acting in the same direction should be added algebraically.

NOTE Recommendations for the design of slabs subject to longitudinal shear are given in 5.3 and 6.3.

5.2.4.2 Serviceability requirements. Except as directed in 5.2.1, the stresses in the concrete slab and reinforcement should be determined by elastic analysis and should not exceed the appropriate limits given in Part 4. Crack widths should be controlled in accordance with 5.2.6.

5.2.4.3 Coexistent stresses. In calculating coexistent stresses in a deck slab, which also forms the flange of a composite beam, account may be taken of the effects of shear lag to reduce the longitudinal bending stress in regions of the flange remote from the web/flange junction. The longitudinal stress f_L , at any point in the flange distance x from the centre line of the web, may be calculated from:

$$f_L = f_{\max} [\chi^4 + k(1 - \chi^4)]$$

where

$$\chi = \left(\frac{b-x}{b} \right)$$

$k = \frac{1}{4} (5\psi - 1)$ for portions between web centre lines, or

$k = \frac{1}{4} (4.25\psi - 1)$ for portions projecting beyond an outer web

$f_{\max}$ is the maximum stress in the concrete flange due to longitudinal bending of the composite section calculated by elastic analysis using the effective flange breadth determined in accordance with 5.2.3

ψ , b are as defined in 5.2.3, and

x is as given in Figure 1

If the calculated value of f_L turns out to be negative it should be taken as zero.

5.2.5 Steel section

5.2.5.1 General. The steel section should be designed in accordance with the recommendations of Parts 3 and 10.

Consideration should be given to the effects noted in 5.2.5.2 to 5.2.5.4.

5.2.5.2 Unpropped construction. Except as noted in 5.2.5.4, where the steel section carries load prior to the development of composite action, the resulting stresses and deflections should be added algebraically to those later induced in the composite member, of which the steel section forms a part, and the appropriate limit states should be satisfied.

5.2.5.3 Propped construction. Where composite action has been assumed for the whole of the design load, consideration should be given to the nature and layout of the props to ensure that the assumptions made in the design will be achieved. Where significant prop settlement cannot be avoided the reduction in propping force should be taken into account.

5.2.5.4 Slab cast in specified sequence. Where the deck slab is cast in a specified sequence the dead load stresses may be calculated on the composite section in accordance with 12.1, using the effective breadth determined from 5.2.3 and the relevant design procedures.

NOTE For the purpose of estimating the effective breadth of the flange, l , in 5.2.3, should be taken as the continuous length of concrete in the flange containing the section under consideration which is assumed to act compositely.

5.2.6 Control of cracking in concrete

5.2.6.1 General. Adequate reinforcement should be provided in composite beams to prevent cracking from adversely affecting the appearance or durability of the structure.

NOTE Special recommendations for cased beams and filler beams are given in clause 8.

5.2.6.2 Loading. In calculating crack widths in reinforced concrete flanges of highway bridges the loading should only comprise dead loading, superimposed dead loading, HA loading (with the HA wheel load excluded except for cantilever slabs, the top flange of beam and slab decks and open-type composite steel box girder bridges) and/or pedestrian loading. In arriving at the design value for the various loads the partial safety factors γ_{f1} and γ_{f2} appropriate to load combination 1 (see Part 2) should be used with γ_{f3} equal to 1.0, except that for HA and HB loading the total partial safety factor on loads $\gamma_{f1} \gamma_{f2} \gamma_{f3}$ should be taken as 1.0, i.e. the nominal load is adopted. For spans less than 6.5 m 25 units of HB loading with associated HA loading should be considered.

For railway loading the values of $\gamma_{f1} \gamma_{f2}$ given in Part 2 with γ_{f3} equal to 1.0 should be used.

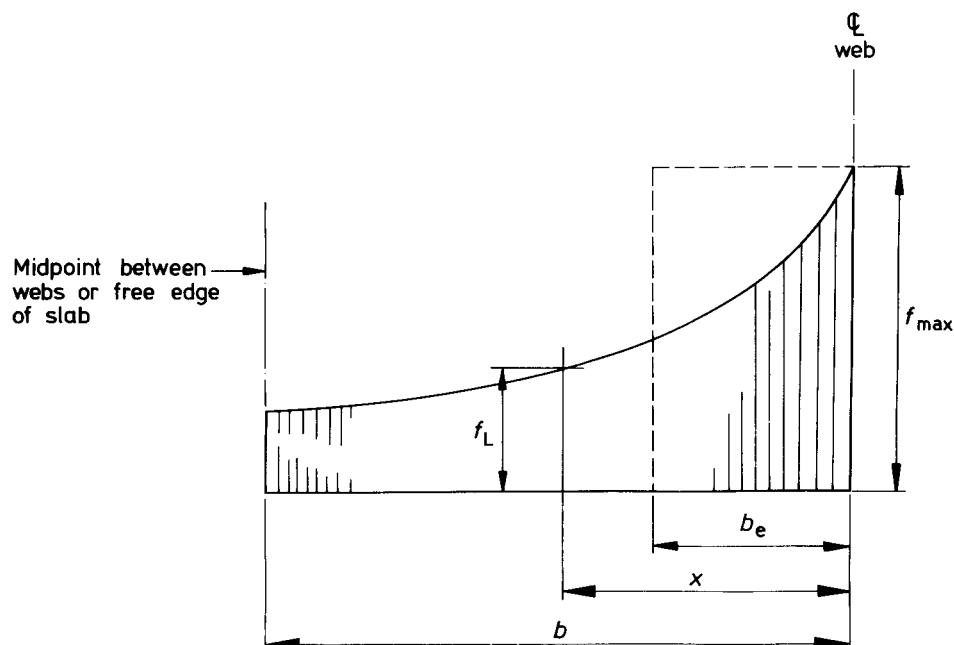


Figure 1 — Distribution of longitudinal stress in the concrete flange of a composite beam

5.2.6.3 Limiting crack width. The engineer should satisfy himself that cracking will not be excessive with regard to the requirements of the particular structure, its environment and the limits to the widths of cracks given in Part 4. Surface crack widths in a composite beam under the action of the loadings specified in 5.2.6.2 may be calculated by the method given in Appendix B. In a concrete flange where the effects of global and local loading coexist the crack width due to global longitudinal bending should be determined in accordance with 5.2.6 and Appendix B. The crack width due to longitudinal local bending in the slab should be determined in accordance with Part 4. The sum of the crack widths due to longitudinal global and local bending, calculated in this manner, should not exceed the appropriate limit. In calculating the strain due to global longitudinal bending account may be taken of the beneficial effect of shear lag in regions remote from the webs in accordance with 5.2.4.3.

5.2.6.4 Maximum distance between bars in tension in highway bridges designed for HA and/or HB loading. Reinforcement provided in accordance with this clause may be deemed to satisfy the recommendations of 5.2.6.3, in respect of composite beams in moderate conditions of exposure, provided the nominal cover to the reinforcement is not greater than 30 mm.

The clear distance between adjacent bars near the tension face of a composite beam should be not greater than the spacing given in Table 5 or Table 6, as appropriate, depending on the stress in the reinforcement at the ultimate limit state and the amount of redistribution carried out in the analysis at the ultimate limit state.

Reinforcement bars of diameter less than 0.45 times the diameter of the maximum size of tension bar at the section considered should be neglected for the purpose of this clause.

5.3 Longitudinal shear

5.3.1 General. Longitudinal shear per unit length of the composite beam q , whether simply supported or continuous, should be calculated for the serviceability limit state on the basis of elastic theory using the properties of the transformed composite cross section calculated assuming the concrete flange to be uncracked and unreinforced. The effective breadth of concrete flange may be assumed to be constant over any span and may be taken as the quarterspan value for uniformly distributed loading given in Table 2, Table 3, or Table 4, as appropriate.

Where the second moment of area of the composite section, thus obtained, varies significantly along the length of any span account should be taken of the variation of stiffness in calculating the longitudinal shear flow.

Table 5 — Clear distance (mm) between bars in tension for propped construction

Stress in reinforcement at ultimate limit state, N/mm^2	Type of analysis at ULS ^a	% redistribution to section considered						
	Uncracked	– 30	– 25	– 20	– 15	– 10	– 5	0
	Cracked	– 20	– 15	– 10	– 5	– 0	+ 5	+ 10
250/ γ_m		200	210	225	235	250	260	275
410/ γ_m		120	130	135	145	150	160	165
460/ γ_m		110	115	120	130	135	140	150

^a Ultimate limit state.

Table 6 — Clear distance (mm) between bars in tension for unpropped construction

Stress in reinforcement at ultimate limit state, N/mm^2	Type of analysis at ULS ^a	% redistribution section considered						
	Uncracked	– 30	– 25	– 20	– 15	– 10	– 5	0
	Cracked	– 20	– 15	– 10	– 5	0	– 5	+ 10
250/ γ_m		230	240	255	270	285	300	300
410/ γ_m		140	150	160	165	175	185	190
460/ γ_m		125	130	140	145	155	165	170

^a Ultimate limit state.

5.3.2 Shear Connectors

5.3.2.1 Nominal strengths of shear connectors embedded in normal density concrete

a) *Static strengths.* Table 7 gives the nominal static strengths of commonly used types of connectors, which are illustrated in Figure 2, in relation to the specified characteristic cube strengths of the normal grades of concrete. The nominal strengths given in Table 7 may be used where the slab is haunched provided that the haunch complies with 6.3.2.1. For other haunches reference should be made to 5.3.2.3.

b) *Fatigue strengths.* The fatigue strength of connectors should be determined in accordance with Part 10.

c) *Strengths of connectors not included in Table 7.* Static strengths should be determined experimentally by push-out tests in accordance with 5.3.2.4. Where the connector type is included in Table 7, but the appropriate size is not given, the fatigue strength should be determined in accordance with Part 10.

5.3.2.2 Nominal strengths of shear connectors embedded in lightweight concrete. The strengths given in a) and b) may be used where the slab is haunched provided that the haunch complies with 6.3.2.1.

NOTE For other haunches see 5.3.2.3.

a) *Static strengths.* The nominal static strengths of headed stud connectors embedded in lightweight concrete of density greater than $1\,400\text{ kg/m}^3$ may be taken as 15 % less than the values given in Table 7. Static strengths of other sizes of stud and of other types of connectors should be determined experimentally by push-out tests made in accordance with 5.3.2.4.

b) *Fatigue strengths.* The fatigue strength of shear connectors embedded in lightweight concrete of density greater than $1\,400\text{ kg/m}^3$ should be determined in accordance with Part 10.

5.3.2.3 Nominal strengths of shear connectors in haunched slabs. Where the haunch does not comply with 6.3.2.1 the nominal static strength of the shear connectors P_u should be determined experimentally by push-out tests (see 5.3.2.4).

The fatigue strength should be determined in accordance with Part 10.

5.3.2.4 Tests on shear connectors

a) *Nominal strength.* The nominal static strength of a shear connector may be determined by push-out tests. Not less than three tests should be made and the nominal static strength P_u may be taken as the lowest value of $f_{cu}P/f_c$ for any of the tests, where P is the failure load of the connectors at concrete strength f_c , and f_{cu} is the specified characteristic cube strength at 28 days.