



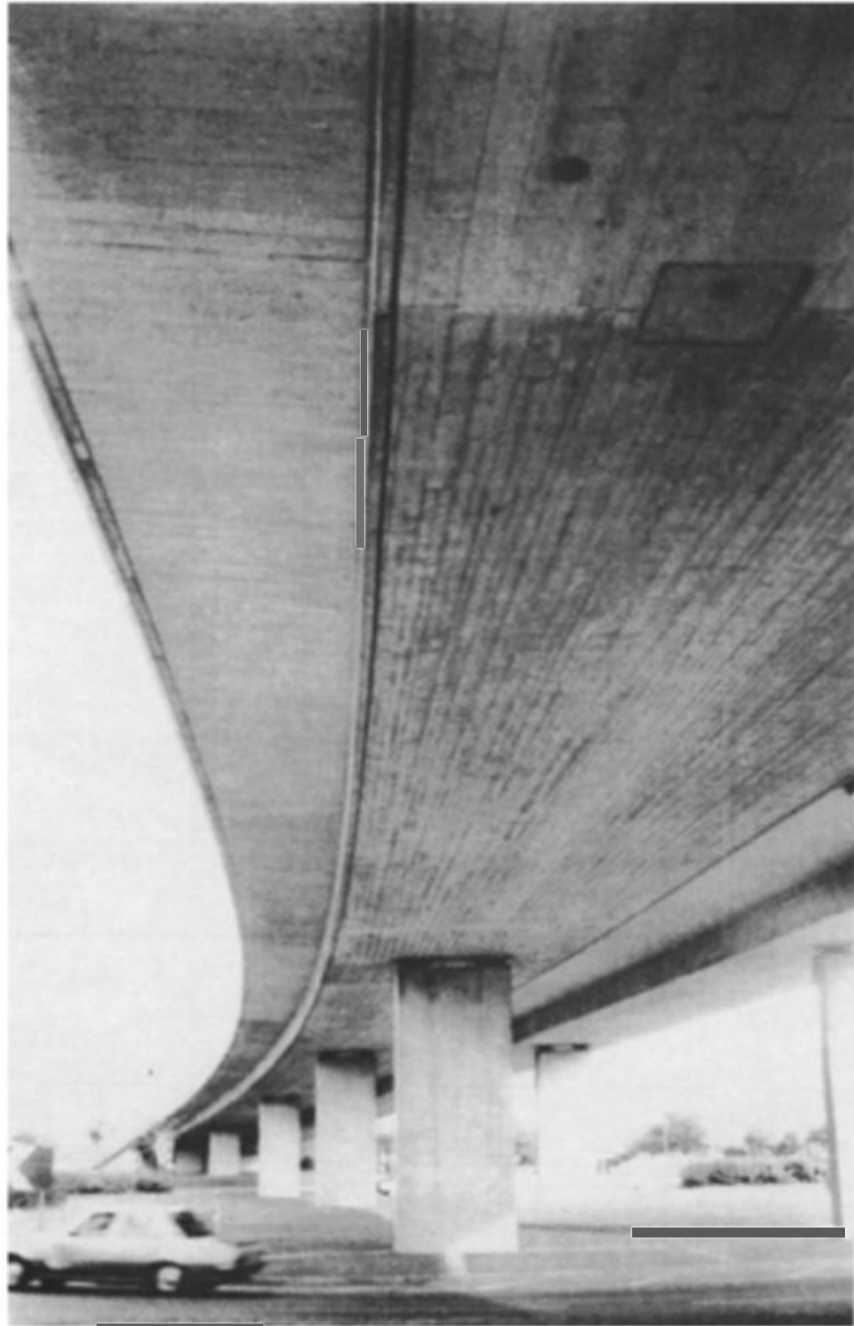
BRIDGE DECK BEHAVIOUR

Second edition

E. C. Hambly

Bridge Deck Behaviour

**Twin-cell concrete
box-girders of Millbrook
Flyover, Southampton,
England; designed by
Gifford and Partners.
Photograph E.C.
Hambly.**



Bridge Deck Behaviour

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This book is dedicated to my wife Elizabeth, without whom it would not exist, and to the late Kenneth H. Roscoe and Stuart G. Spickett from whom we both continue to draw inspiration.



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Contents

Acknowledgements	xi
Preface	xiii
Notation	xvii
1. Structural forms and calculation methods	1
1.1 Introduction	1
1.2 Structural forms	2
1.3 Safety of methods	17
1.4 Hooke's law and Young's modulus	21
References	22
2. Beam decks and frames	24
2.1 Introduction	24
2.2 Types of beam deck	24
2.3 Bending of beams	26
2.4 Torsion of beams	39
2.5 Computer analysis of continuous beams	45
2.6 Construction sequence	45
2.7 Frame and arching action	47
2.8 Short-term and long-term behaviour	50
References	52
3. Slab decks	53
3.1 Introduction	53
3.2 Types of structure	53
3.3 Structural action	55
3.4 Rigorous analysis of distribution of forces	61
3.5 Grillage analysis	61
3.6 Grillage examples	68
3.7 Interpretation of output	72
3.8 Moments under concentrated loads	73

3.9	Shear-key slab decks	74
3.10	Grillage analysis of shear-key slab	75
	References	81
4.	Beam-and-slab decks	82
4.1	Introduction	82
4.2	Types of structure	83
4.3	Structural action	83
4.4	Grillage analysis	85
4.5	Grillage examples	89
4.6	Application of load	92
4.7	Interpretation of output	94
4.8	Torsionless design	95
4.9	Bracing	99
4.10	Slab membrane action in beam-and-slab decks	102
	References	104
5.	Multicellular decks	106
5.1	Introduction	106
5.2	The shear-flexible grillage	106
5.3	Grillage mesh	107
5.4	Modes of structural action	108
5.5	Section properties of grillage members	122
5.6	Load application	127
5.7	Interpretation of output	127
5.8	Comparison with finite strip method	132
	References	133
6.	Box-girder decks	135
6.1	Distortion of single-cell box-girder	135
6.2	Methods of calculation	137
6.3	BEF analysis of box-girder	137
6.4	Space frame analysis of box-girder	141
6.5	Grillage analysis of box-girder	145
6.6	Grillage analysis of multiple box-girder deck	149
6.7	Grillage analysis of a multispan box-girder	151
	References	156
7.	Space frame methods and slab membrane action	157
7.1	Truss space frame	157
7.2	McHenry lattice	160
7.3	Cruciform space frame	161
7.4	Slab membrane action	165
7.5	Downstand grillage	167

7.6	Effects of slab membrane action on beam-and-slab deck behaviour	174
	References	176
8.	Shear lag and edge stiffening	177
8.1	Shear lag	177
8.2	Effective width of flanges	177
8.3	Edge stiffening of slab decks	182
8.4	Upstand parapets to beam-and-slab decks	183
8.5	Service bays in beam-and-slab decks	185
	References	187
9.	Skew, tapered and curved decks	188
9.1	Skew decks	188
9.2	Tapered decks	192
9.3	Curved decks	193
	References	198
10.	Distribution coefficients	199
10.1	Introduction	199
10.2	Some published load distribution charts	200
10.3	Influence lines for slab, beam-and-slab and cellular decks	205
10.4	Application of charts to slab deck	208
10.5	Application of charts to beam-and-slab deck	213
10.6	Application of charts to cellular deck	216
	References	221
11.	Temperature and prestress loading	222
11.1	Introduction	222
11.2	Temperature strains and stresses in simply supported span	222
11.3	Temperature stresses in a continuous deck	227
11.4	Grillage analysis of temperature moments	229
11.5	Differential creep and shrinkage	230
11.6	Prestress axial compression	231
11.7	Prestress moments due to cable eccentricity	233
11.8	Prestress moments due to cable curvature	234
11.9	Prestress analysis by flexibility coefficients	236
11.10	Prestress applied directly to space frame	238
	References	242
12.	Harmonic analysis and folded plate theory	244
12.1	Introduction	244

12.2	Harmonic components of load, moment, etc	245
12.3	Characteristics of low and high harmonics	249
12.4	Harmonic analysis of plane decks	253
12.5	Folded plate analysis	255
12.6	Continuous and skew decks	260
12.7	Errors of harmonics near discontinuities	261
	References	262
13.	Finite element method	263
13.1	Introduction	263
13.2	Two-dimensional plane stress elements	264
13.3	Plate bending elements	271
13.4	Three-dimensional plate structures and shell elements	275
13.5	Finite strips	276
13.6	Three-dimensional elements	278
13.7	Conclusion	279
	References	280
14.	Stiffnesses of supports and foundations	281
14.1	Introduction	281
14.2	Substructures and bearings	282
14.3	Foundation stiffnesses	283
14.4	Stiffness moduli of soils	290
14.5	Stiffnesses from lateral earth pressures	291
14.6	Embankment movements	293
14.7	Integral bridges	294
	References	299
	Appendix A	301
	Product integrals. Functions of load on a single span. Harmonic components	
	Appendix B	305
	Calculation of torsion constant for solid beams	
	Author Index	307
	Subject Index	309

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E.C.H.



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Preface

This book describes the load distribution behaviour of steel and concrete bridge decks. The principles can also be applied to several other materials and deck-type structures. The book has been written to be intelligible to junior engineers who are interested in the physical characteristics of the different types of construction and who require detailed descriptions of some calculation methods. The book has also been written with consideration for the senior engineers leading design teams, to give them information about the range of analytical methods available and on some of their shortcomings. It has been assumed that the design and assessment of bridges are entrusted to experienced professional civil engineers, and that calculations are carried out under the direction of appropriately experienced and qualified supervisors. Users of this book are expected to draw upon other works on the subject including national and international codes of practice, and are expected to verify the appropriateness and content of information they draw from this book.

In this second edition, Chapter 1 has been enlarged to explain the intrinsic safety of some calculation methods when used in a systematic manner. Chapter 2 on beam decks and frames now includes demonstrations of the influence of foundation stiffnesses on the frame behaviour of a portal bridge and an arching structure. Chapter 3 on slabs now includes the analysis of shear-key decks. Chapter 4 on beam-and-slab bridges has been enlarged with new sections on 'torsionless design' which can simplify the design of some bridges, and on bracing of steel beams. New examples illustrate the grillage analysis of a composite bridge using AASHTO-type prestressed concrete girders, and of a composite steel deck. Chapter 5 on cellular structures includes additional comparisons between grillage and finite strip analyses.

A new Chapter 6 explains the distortion of box-girder bridges. Examples illustrate the analysis of box girders by beams-on-elastic-foundations, two types of grillage and space frame models. In recent

years the author has made increasing use of simple space frame idealizations of three-dimensional structures, and Chapter 7 has been enlarged to demonstrate their wide range of applications. The discussion of shear lag and edge stiffening in Chapter 8 has additional comments on load redistribution. Chapter 9 on skew and curved decks illustrates the interaction of bending and torsion in a space frame analysis of a curved multispan bridge. Chapter 11 on temperature and prestress has been enlarged to demonstrate the use of space frame models for calculation of the effects of temperature and prestress. A new example illustrates the effects of post-tensioning on the torsion and bending of a curved multispan bridge. Prestress and other internal loads can be applied directly to the computer model, in the same manner as to the real structure, so that it is not necessary to calculate equivalent loads or to separate the effects into 'primary' and 'secondary'.

A new Chapter 14 has been included on the stiffnesses of supports and foundations. The stiffnesses of supports and foundations are becoming increasingly important as bridge engineers turn to integral bridge designs with no movement joints in order to reduce maintenance problems. A worked example illustrates the global analysis of an integral bridge, including deck, supports and ground. Appendix B explains the calculation of torsion stiffness.

The overall objectives of the second edition, like the first, have been to explain and demonstrate the underlying principles of different bridge types. Each designer can apply them to suit the particular bridges, computer programs and design codes relevant to his or her part of the world.

The book shows how complex structures can be analysed with physical reasoning and relatively simple computer models, and without complicated mathematics. In recent years the computer methods of grillage and space frame have become very popular and accessible as microcomputers and software have developed rapidly. The visual displays of modern programs can provide an engineer with a comprehensive picture and understanding of the behaviour of his structure. At the design stage this helps him to manipulate his design and so economize in the use of construction materials. During the assessments of old bridges he can examine alternative load paths with ease and so determine the reserves of strength as the structure changes. The improvements in facilities since the publication of the first edition now enable the author to analyse in one hour a deck which previously took several days.

Engineers, in general, have confidence in their calculations only when they can back them up with physical reasoning. For this reason this book concentrates on the physical reasoning that is necessary to translate prototype behaviour and properties into computer models,

and vice versa. Most attention is paid to the simpler methods of grillage and space frame because they are more commonly used. With experience engineers are able to use physical reasoning and simple models for the design of relatively complex structures. However, since such experience involves comparisons of results of these simple methods with test results and solutions of more rigorous analyses, the principles of space frame, folded plate and finite element methods are described in later chapters. The only mathematics that is necessary for the majority of bridge deck designs is summarized in Chapter 2 and concerns simple beam theory that is covered in most university first year courses on civil and structural engineering.

Hand methods of analysis are also very useful and will remain essential for preliminary design, checks, and when the computer is not available. Initially the author greatly preferred such methods to the general use of the computer, and an early draft of this book concentrated on the subject. However with increased experience and responsibility, a complete change of attitude became necessary because the computer methods had the following advantages.

1. They are comprehensible to the majority of engineers, many of whom, though thoroughly competent, do not have the mathematical expertise in techniques, such as harmonic analysis, that are needed for accurate application of many hand methods to complicated structures.
2. They are applicable to the majority of bridge shapes with skew, curved or continuous decks and with varying stiffness from region to region. In contrast, hand methods are simple to use only for the few bridges which are rectangular in plan and simply supported.
3. They are also applicable, with shear flexibility, to a much wider variety of deck cross-sections.
4. They are checkable; it is much easier to check computer data and output distributions of forces than pages of hand calculations.
5. Finally, they are economical. With the development of very convenient and clear grillage programs computer data can be prepared, numerous load cases analysed, and the results processed in a much shorter time than the equivalent hand calculations can be carried out.

None the less, because hand methods are still very useful, some published techniques are reviewed in Chapter 10 and applications of rapid design charts are demonstrated.

The accuracy of any method of analysis for a particular structure is difficult to predict or even check. It depends on the ability of the model to represent three very complex characters: the behaviour of the material, the geometry of the structure, and the actual loading.

Construction materials, even when homogeneous, have properties differing widely from the elastic, or plastic idealizations. When incorporated in a structure they have innumerable variations of stiffness and strength owing to composition, and site and life histories. The analysis almost invariably simplifies the geometry of the structure of thick members to an assemblage of thin plates or beams. Numerous holes, construction joints, site imperfections and other details are ignored. Finally the design loadings for live load, temperature, creep, settlement and so on are idealizations based on statistical studies. It is unlikely that the critical design load will ever act on the structure even though it might be exceeded. For these reasons, large errors are likely whatever method of analysis is used. It is suggested that greater emphasis should be given to considering the physical behaviour of the structure and anticipating consequences of calculations being in error by more than 20% than to refining calculations in pursuit of the last 1% of apparent accuracy.

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September 1990

Notation

Superscripts

-	average value or global variable
^	maximum value
'	relates to top slab of cellular deck
"	relates to bottom slab of cellular deck

Subscripts

b	BEF-equivalent beam
c	about centroid, or complete section
e	of equivalent grillage member, or of effective flange
f	of flange
l	longitudinal
M	due to bending
S	due to shear
T	due to torsion
t	transverse
u	undrained
W	related to loading
w	of web
x, y, z	axis of member, or moment, force or section property related to vertical bending of that member
xx, yy, zz	local axis for direction of force and associated shear area or about which moment acts
I, II	principal values
$1, 2, \dots, n$	number of end, or slab edge, or support, or node, or beam, or harmonic
A	area of, cross-section, or part section, or enclosed area
A_S	equivalent shear area
a	stiffness coefficient, or dimension, or harmonic coefficient
a_S	equivalent shear area per unit width

BEF	beam-on-elastic-foundations
<i>b</i>	breadth, or stiffness coefficient, or harmonic coefficient
<i>C</i>	torsion constant
<i>c</i>	torsion constant per unit width, or stiffness coefficient
<i>c</i>	cellular stiffness ratio
<i>D</i>	flexural rigidity
<i>d</i>	depth, or thickness
<i>E</i>	Young's modulus
<i>e</i>	eccentricity of prestress
<i>F</i>	node force
<i>f</i>	flexural stiffness ratio
<i>G</i>	shear modulus
<i>g</i>	stiffness coefficient
<i>H</i>	abutment height
<i>h</i>	distance between midplanes of slabs in cellular decks
<i>h', h''</i>	distances of midplanes of top and bottom slabs from their common centroid
<i>I</i>	moment of inertia = second moment of area
<i>i</i>	moment of inertia per unit width
<i>J</i>	influence value
<i>j</i>	shear flexibility parameter
<i>K, k</i>	stiffness matrices
<i>k</i>	spring stiffness, or stiffness coefficient
<i>L</i>	span, or distance between points of contraflexure
<i>l</i>	length, or web, or 'beam' spacing, or BEF panel length
<i>M</i>	bending moment
<i>M_{FE}</i>	fixed end moment
<i>m</i>	moment per unit width, or modular ratio, or moment system in flexibility analysis
<i>N</i>	applied torque
<i>n</i>	harmonic number, or stiffness coefficient
<i>O</i>	origin
<i>P</i>	force, or prestress compression force, or passive soil force
<i>q</i>	BEF bracing stiffness
<i>R</i>	radius of curvature, or reaction
<i>r</i>	force matrices
<i>r</i>	shear flow
<i>r</i>	rotational stiffness ratio
<i>S</i>	shear force
<i>S_{FE}</i>	fixed end shear force
<i>S_U</i>	soil undrained strength
<i>s</i>	shear force per unit width, or distance around curved arc or midplane

T	torque
t	torque per unit width, or thickness
t	axis rotation transformation matrix
U	applied load in Ox direction
u	displacement in Ox direction (warping)
U, u	force or displacement matrices
V	applied load in Oy direction
v	displacement in Oy direction, or BEF out-of-plane shear/ torsion
W	applied load in Oz direction (vertical downwards), or BEF deflection
w	displacement in Oz direction (vertical downwards), or BEF deflection
Ox	horizontal axis along span (except where given local direction)
X, x	release action in flexibility analysis
X	load matrix
Oy	horizontal axis transverse to span (except where given local direction)
y	horizontal distance of point to side of origin or neutral axis
Z	amplitude of harmonic component of vertical load
Oz	vertical axis downwards (except where given local direction)
z	vertical distance of point below origin or neutral axis
α	angle, or coefficient of thermal expansion, or $(n\pi/L)$
$\alpha_1, \alpha_2, \dots$	coefficients of displacement field
β	BEF parameter
γ	shear strain, or soil density
Δ	increment
δ	flexibility coefficient, or displacement
ε	linear strain
θ	rotation, usually slope $\partial w/\partial x$, or inclination of prestress
ν	Poisson's ratio
σ	tension/compression stress
τ	shear stress
ϕ	rotation, usually $\partial w/\partial y$, or soil angle of friction, or creep factor
$\dot{\phi}$	twist = rate of change of ϕ with length

Units

The examples in this book use SI metric units.

Dimensions are generally expressed in metres (m) where

$$1 \text{ m} = 3.28 \text{ ft}$$

Forces are generally expressed in meganewtons (MN) where

$$1 \text{ MN} = 100 \text{ tons.}$$

Stresses and pressures are expressed in megapascals (MPa) or meganewtons per square metre (MN/m^2), which is the same as newtons per square millimetre (N/mm^2).

$$1 \text{ MPa} = 1 \text{ MN/m}^2 = 1 \text{ N/mm}^2 = 145 \text{ psi.}$$

and calculation methods

1.1 INTRODUCTION

Bridge decks are developing today as fast as they have at any time since the beginning of the Industrial Revolution [1–4]. The diversity of sites is increasingly challenging the ingenuity of engineers to produce new structural forms and appropriate materials. Methods of analysis have developed equally rapidly, particularly with the use of computer methods. The accessibility of microcomputers is making it progressively easier for engineers to analyse bridges with complex cross-sections and complicated skew, curved and continuous spans. In the past a considerable amount of theoretical and experimental research was required to develop the design methods. Today, however, several have been developed to such usable form that, with an understanding of physical behaviour, designers can analyse complex decks without recourse to complicated mathematical theory.

This book concentrates on the simpler computer methods of calculation of grillage and space frame. Section 1.3 explains the merits and intrinsic safety of the methods when used in a systematic manner. One of the most useful aspects of the methods is that each part of a structure is represented by equivalent beam elements. Most structural engineers have an intuitive feel for how beams react to the various forces of bending, shear and torsion, and they can use physical reasoning. A simple physical model, such as illustrated in Fig. 1.2, is often more reliable than complicated calculations as a guide to the size and directions of forces and displacements.

Section 1.2 reviews and categorizes the principal types of bridge deck that are currently being used, and refers to the analytical techniques demonstrated in later chapters. The types of bridge deck are divided into beam, grid, slab, beam-and-slab and cellular, to differentiate their individual geometric and behavioural characteristics. Inevitably many decks fall into more than one category, but they can usually be analysed



Fig. 1.1 Wrought iron box girders of 140 m span of Britannia Bridge, Wales, 1849; designed by Robert Stephenson. Lithograph from Cyclopaedia of Useful Arts by C. Tomlinson, 2nd edn, 1866. Photograph courtesy of Elton Engineering Books.

by using a judicious combination of the methods applicable to the different types.

1.2 STRUCTURAL FORMS

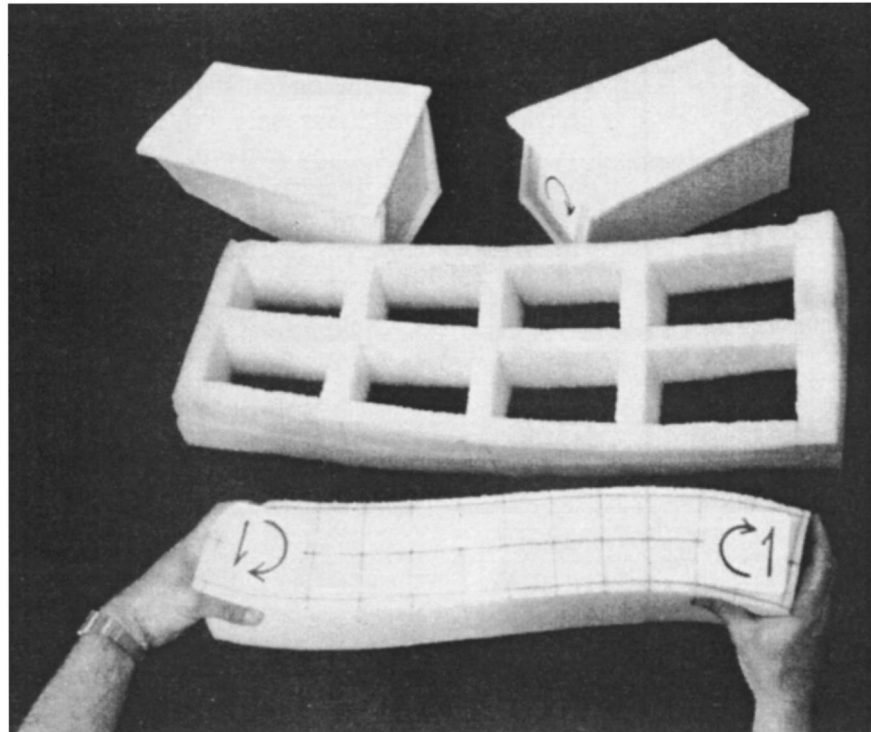
1.2.1 Beam decks

A bridge deck can be considered to behave as a beam when its length exceeds its width by such an amount that when loads cause it to bend and twist along its length, its cross-sections displace bodily and do not change shape, as shown in Fig. 1.3.

The most common beam decks are footbridges, either of steel, reinforced concrete or prestressed concrete. They are often continuous over two or more spans. Many long-span bridges behave as beams because the dominant load is concentric so that the distortion of the cross-section under eccentric loads has relatively little influence on the principal bending stresses.

The analysis of bending moments and torsions in continuous beam decks is discussed in Chapter 2. Frame action is also discussed for decks

Fig. 1.2 Physical models for understanding distributions of forces and displacements.



in which the stiffness and geometry of the supports have a significant influence on behaviour.

1.2.2 Grid decks

The primary structural member of a grid deck is a grid of two or more longitudinal beams with transverse beams (or diaphragms) supporting the running slab. Loads are distributed between the main longitudinal beams by the bending and twisting of the transverse beams, as shown in

Fig. 1.3 Beam deck bending and twisting without change of cross-section shape.

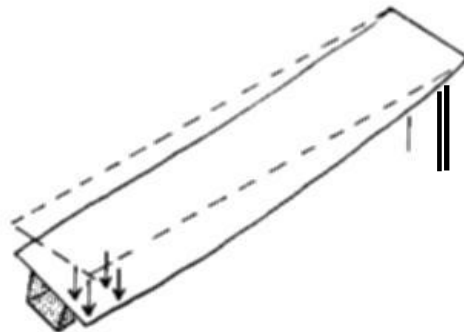


Fig. 1.5. Because of the amount of workmanship needed to fabricate or shutter the transverse beams, this method of construction is becoming less popular and is being replaced by slab and beam-and-slab decks with no transverse diaphragms.

Grid decks are most conveniently analysed with the conventional computer grillage analysis described in Chapter 4. The analysis in effect

Fig. 1.4 Concrete box girder Kocher Viaduct, Geislingen, Germany; designed by Prof. Peter Bonatz of Wayss & Freytag, Frankfurt, with Leonhardt and Andra as advisor and Prufingenieur. Photograph courtesy of Prof. Fritz Leonhardt.

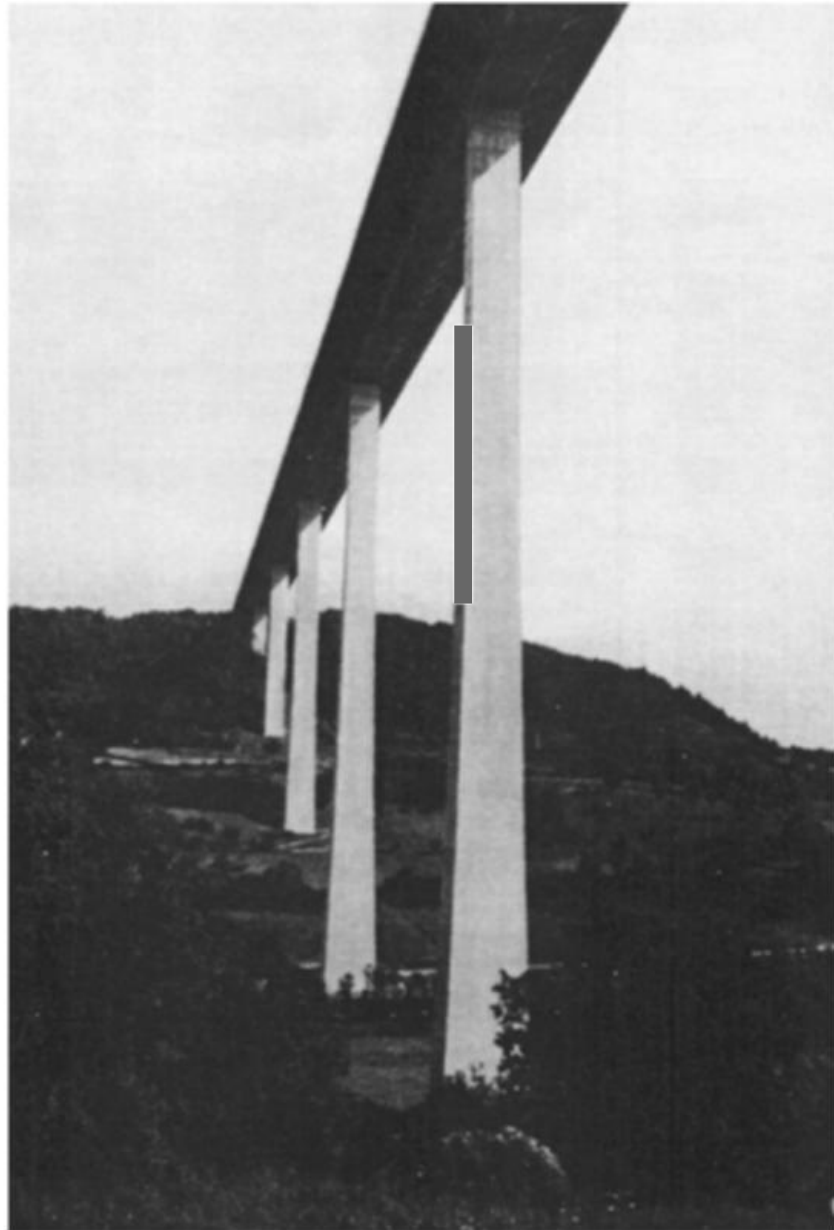
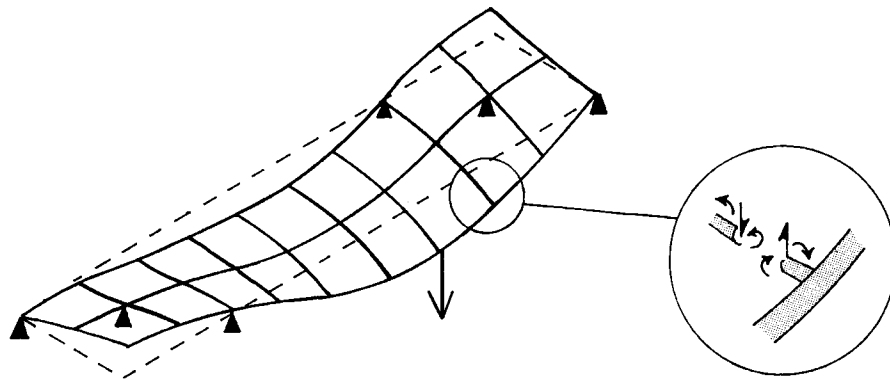


Fig. 1.5 Load distribution in grid deck by bending and torsion of beam members.

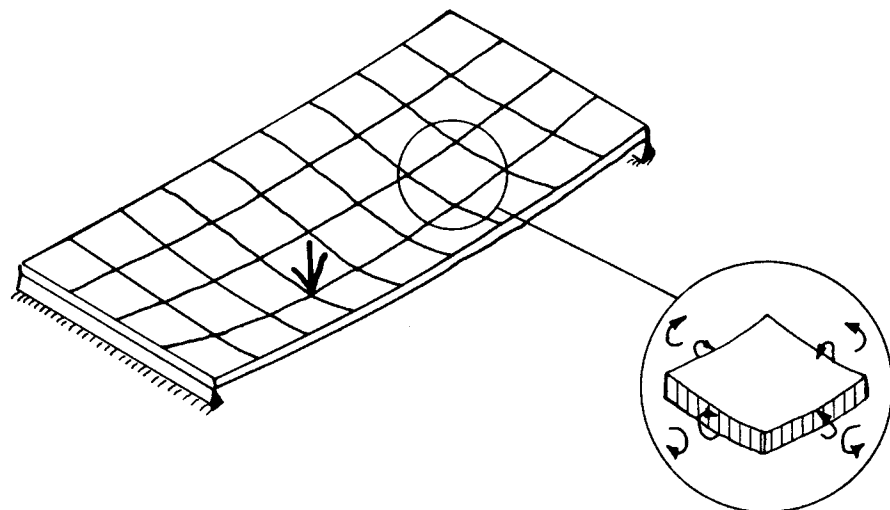


sets out a set of simultaneous slope-deflection equations for the moments and torsions in the beams at each joint and then solves the equations for the load cases required. Grid decks have also been analysed for many years by hand methods which are summarized in Chapter 10. However, such methods are decreasing in popularity as computer methods become simpler and more versatile.

1.2.3 Slab decks

A slab deck behaves like a flat plate which is structurally continuous for the transfer of moments and torsions in all directions within the plane of the plate. When a load is placed on part of a slab, the slab deflects locally in a 'dish' causing a two-dimensional system of moments and torsions which transfer and share the load to neighbouring parts of the deck which are less severely loaded, as shown in Fig. 1.6. A slab is 'isotropic'

Fig. 1.6 Load distribution in slab deck by bending and torsion in two directions.



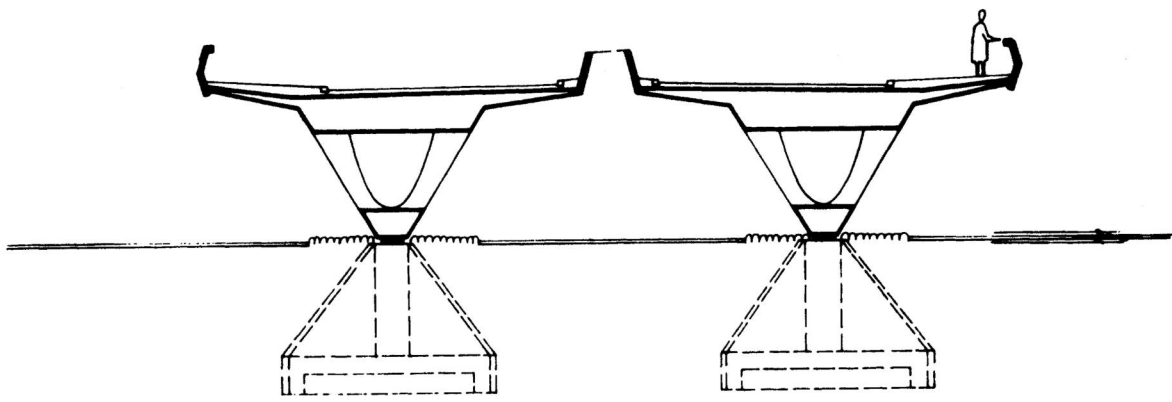
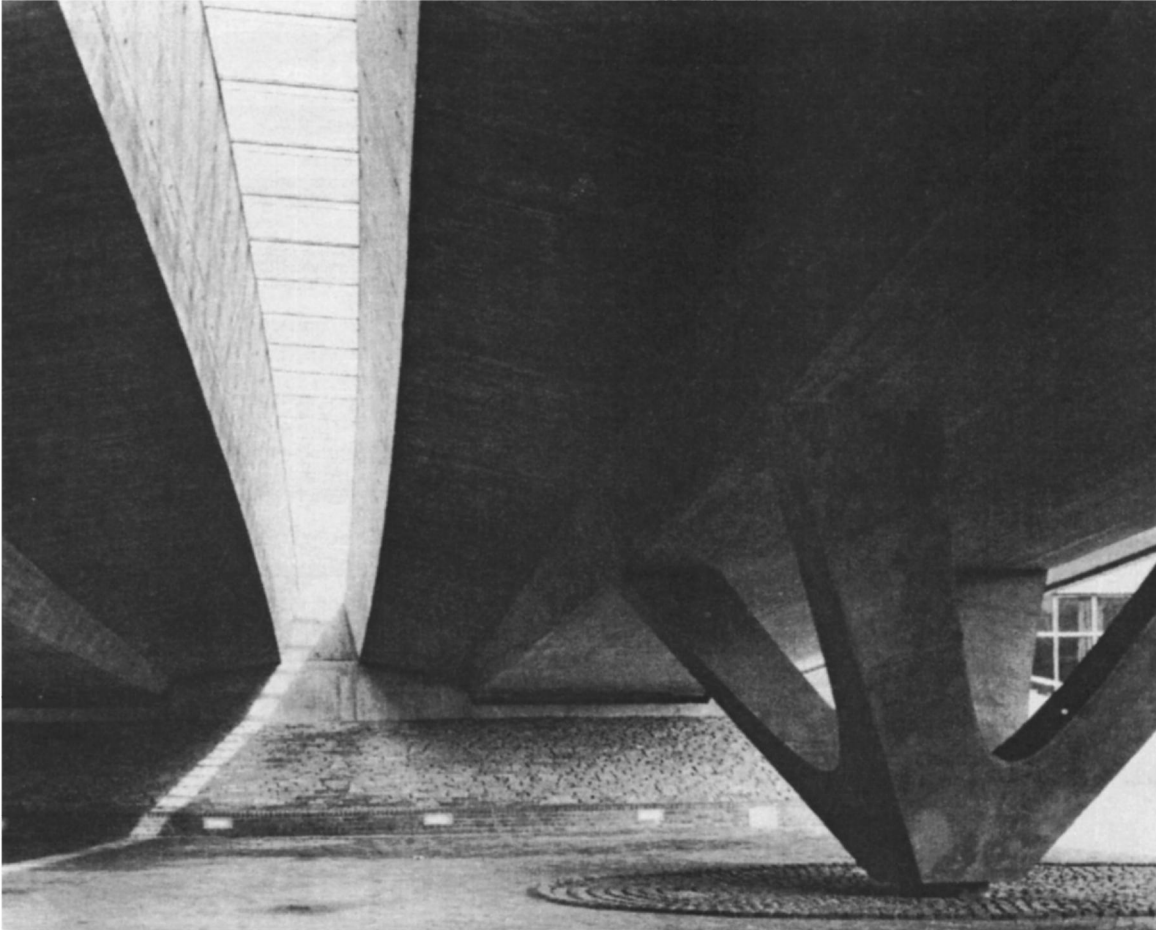


Fig. 1.7 Concrete slab decks of Western Bank Bridge, Sheffield, England; designed by Ove Arup & Partners. Photograph courtesy Ove Arup & Partners.

when its stiffnesses are the same in all directions in the plane of the slab. It is 'orthotropic' when the stiffnesses are different in two directions at right angles.

Concrete slab decks are commonly used where the spans are less than 15 m (50 ft). If the deck is cast *in situ* it is general practice to consider it as isotropic, even though the reinforcement may not be the same in all directions.

When it is inconvenient to support the deck on falsework during construction, the slab is often built compositely with reinforced concrete cast *in situ* between previously erected beams, as shown in Fig. 1.8(b). The beams of precast concrete or steel have a greater stiffness longitudinally than the *in situ* concrete has transversely; thus the deck is orthotropic.

For spans greater than 15 m (50 ft), the material content and dead load of a solid slab become excessive and it is customary to lighten the structure by incorporating voids of cylindrical or rectangular cross-section near the neutral axis. These are shown in Fig. 1.8(c) and (d). If the depth and width of the voids are less than 60% of the overall structural depth, their effect on the stiffness is small and the deck behaves effectively as a plate. Voided slab decks are frequently constructed of concrete cast *in situ* with permanent void formers, or of precast prestressed concrete box beams post-tensioned transversely to ensure transverse continuity. If the void size exceeds 60% of the depth, the deck is generally considered to be of cellular construction with a different behaviour, as is described later.

Rigorous analysis of most slab decks is not possible at present. However, slab decks can be conveniently analysed using the computer grillage as described in Chapter 3. In this method the continuous slab is represented by an equivalent grid of beams whose longitudinal and transverse stiffnesses are approximately the same as the local plate stiffnesses of the slab. This analogy is not the closest available, but it has been found to agree well with more rigorous solutions and is generally

Fig. 1.8 Slab decks: (a) solid; (b) composite of *in situ* concrete in-filling precast beams; (c) voided; and (d) voided of precast box beams post-tensioned transversely.

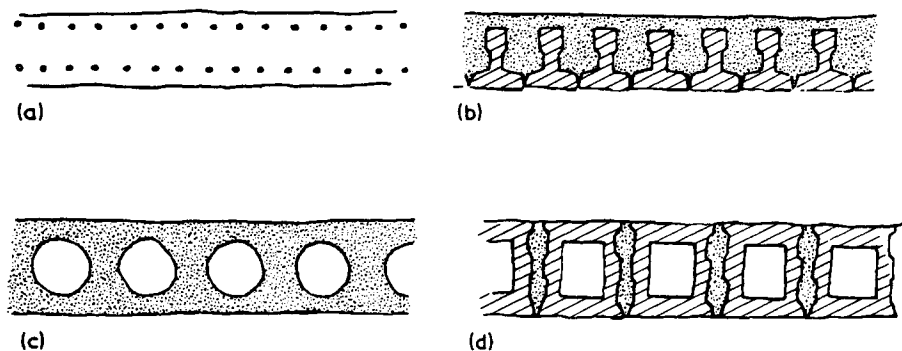
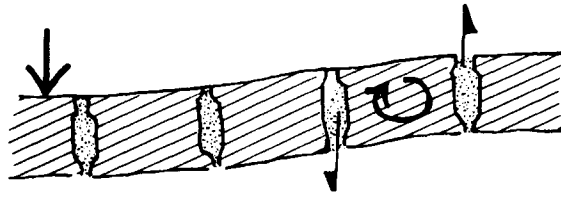


Fig. 1.9 Differential deflections of beams in shear-key deck resisted by torsion of beams.



accepted as sufficiently accurate for most designs. One of the more exact methods, which is mentioned in Chapter 13, is performed using a computer finite element program. In this method the deck is notionally split up into a number of elements, frequently triangular, for each of which approximate plate bending equations can be derived and solved (as opposed to the beam equations used in the grillage). The method is much more complicated and expensive than the grillage, and since for slab decks it does not generally produce significantly different results, the grillage is normally used in preference. The hand methods of Chapter 10 also provide a convenient method of analysis for the design of slab decks with simple plan geometry. However, as mentioned for grid decks, computer methods are becoming easier to use and provide more information.

One type of deck which does not fit neatly into any of the main categories is the 'shear-key' deck. A shear-key deck is constructed of contiguous prestressed/reinforced concrete beams of rectangular or box sections, connected along their length by *in situ* concrete joints. It is not prestressed transversely and thus is not fully continuous for transverse moments. The main application is for bridges constructed over busy roads or railways, where it is convenient to erect the beams overnight and then complete the jointing without disturbance to the traffic below. Although such decks have little or no transverse bending stiffness, distribution of loads between beams still takes place because differential deflection of the beams is resisted by the torsional stiffness of the beams and a vertical shear force is transferred across the keyed joints. The analysis of such decks is described in Chapter 3.

1.2.4 Beam-and-slab decks

A beam-and-slab deck consists of a number of longitudinal beams connected across their tops by a thin continuous structural slab. In transfer of the load longitudinally to the supports, the slab acts in concert with the beams as their top flanges. At the same time the greater deflection of the most heavily loaded beams bends the slab transversely so that it transfers and shares out the load to the neighbouring beams. Sometimes this transverse distribution of load is assisted by a number of transverse diaphragms at points along the span, so that deck behaviour

is more similar to that of a grid deck. However, the use of diaphragms is becoming less popular because of the construction problems they cause and because their localized stiffnesses attract forces which can cause unnecessary stress concentrations. Beam-and-slab construction has the advantage over slab that it is very much lighter while retaining the necessary longitudinal stiffness. Consequently it is suitable for a much wider range of spans, and it lends itself to precast and prefabricated construction. Occasionally, the transverse flexibility can be advantageous; for example, it can help a deck on skew supports to deflect and



Fig. 1.10 Steel composite beam-and-slab bridge at Newburgh, Scotland; designed by Grampian Regional Council. Photograph courtesy Grampian Regional Council.

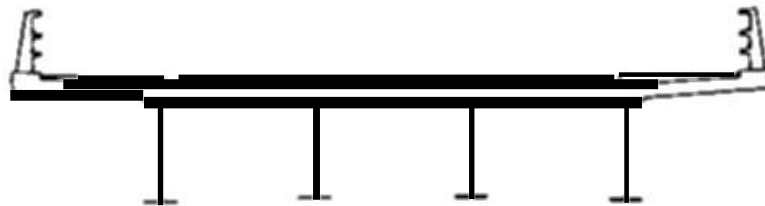
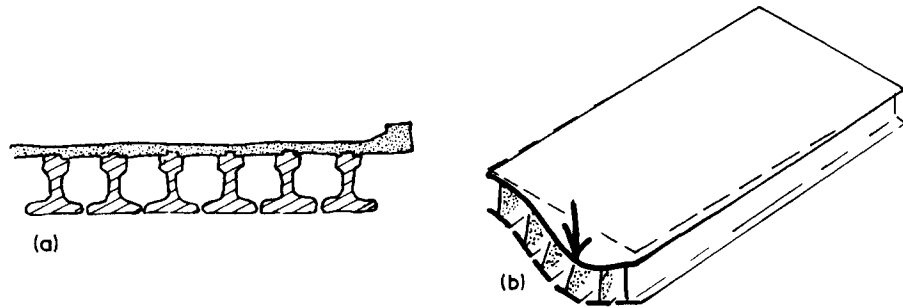


Fig. 1.11 (a) Contiguous beam-and-slab deck and (b) slab of contiguous beam-and-slab deck deflecting in smooth wave.

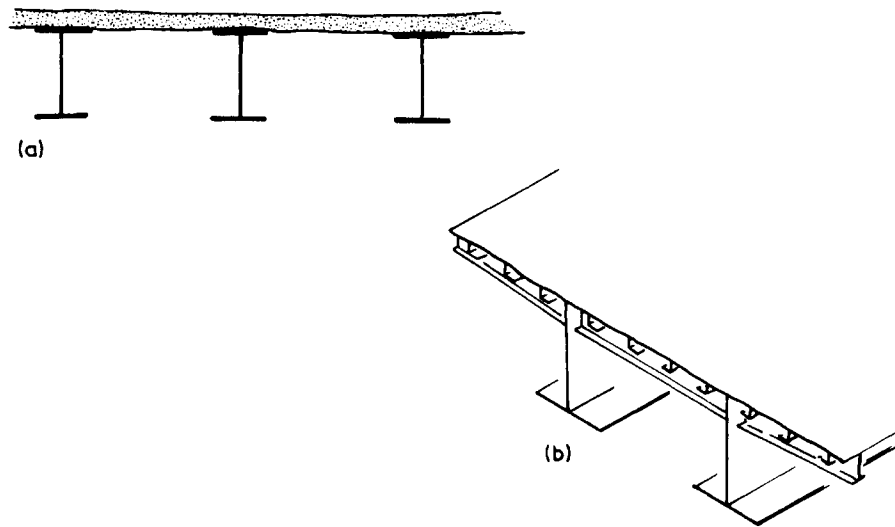


twist 'comfortably' under load without excessively loading the nearest supports to the load or lifting off those further away.

Beam-and-slab decks can be divided into two main groups: those with the beams at close centres or touching are referred to as 'contiguous beam-and-slab', while those with beams at wide centres are referred to as 'spaced beam-and-slab'. The most common form of contiguous beam-and-slab, shown in Fig. 1.11, comprises precast prestressed concrete inverted T-beams supporting a cast *in situ* reinforced concrete slab of about 200 mm (8 in) thickness. When a load is placed on part of such a deck, the slab deflects in a smooth wave so that for load distribution its behaviour can be considered similar to that of an orthotropic slab with longitudinal stiffening.

Spaced beam-and-slab decks shown in Fig. 1.12 commonly have the beams at about 2 m (6 ft) to 3.5 m (12 ft) centres. Decks have been designed with precast prestressed concrete beams or steel beams supporting a concrete slab. Numerous variations of construction have

Fig. 1.12 Spaced beam-and-slab decks with steel I-beams and (a) concrete slab (b) steel 'battledack' running slab.



been employed for the concrete slab ranging from totally cast *in situ* to very large precast panels connected to the beams by the minimum of *in situ* concrete in the joints. Sometimes the running slab on steel beams consists of a steel 'battledack' which is constructed of a stiffened steel plate of as little as 12 mm ($\frac{1}{2}$ in) thickness. When a load is placed above one beam of a spaced beam-and-slab deck, the slab does not necessarily deflect transversely in a single wave but sometimes in a series of waves between beams. This is particularly the case if the beams have high torsional stiffnesses, as do box beams, when the beams may twist little so that the slab deflects in a series of transverse steps as shown in Fig. 1.13. Such behaviour is different from that of orthotropic slabs and it is advisable for the analytical model to have its high longitudinal beam stiffnesses correctly positioned across the deck. If the various stiffnesses cannot be correctly located, the load distribution analysis is sometimes backed up with a plane frame analysis of the cross-section to study its transverse bending and distortion.

The extreme form of spaced beam-and-slab decks can have as few as two spine beams at more than 12 m (40 ft) centres. Solid concrete spines at more than 7 m (24 ft) are rare, but twin-spine concrete and steel box-girder decks are not uncommon. While the bending and torsional behaviour of the spines must be considered as described below for cellular decks, the distribution of loads between spines is essentially beam-and-slab.

Beam-and-slab decks are most conveniently analysed with the aid of conventional computer grillage programs, as mentioned for slab decks above. The application of this method to these decks is described in Chapter 4. This method is generally accepted as sufficiently accurate for design, but it ignores possible high horizontal shear forces in the slab resulting from differences in the shortening of the top fibres of adjacent beams subjected to different bending deflections. Methods for assessing these forces are described in Chapter 7.

Fig. 1.13 Spaced beam-and-slab deck deflecting in a series of steps or waves.

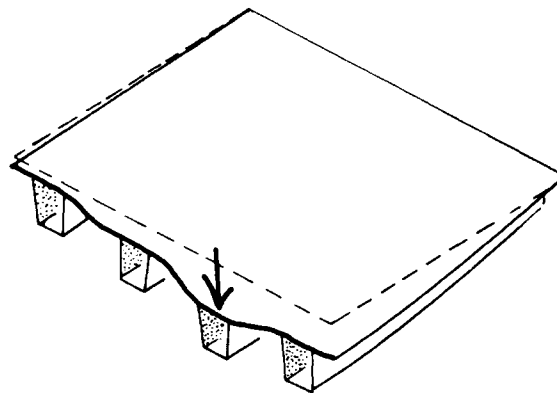


Fig. 1.14 Steel box girder composite bridge at Nashville, Tennessee, USA; designed by State of Tennessee Department of Transportation. The 54 m centre span has short end spans built into the abutments to form an integral bridge with no movement joints between embankments. Photograph courtesy of George Hornel, State of Tennessee.

1.2.5 Cellular decks

The cross-section of a cellular or box deck is made up of a number of thin slabs and thin or thick webs which totally enclose a number of cells. These complicated structural forms are increasingly used in preference to beam-and-slab decks for spans in excess of 30 m (100 ft) because in addition to the low material content, low weight and high longitudinal bending stiffness they have high torsional stiffnesses which give them better stability and load distribution characteristics. The use of box decks has been particularly spectacular in recent years for long, high spans, where falsework is inappropriate, and the deck has been erected in elements as a beam cantilevering out from supports or the deck has been constructed and launched across the piers from an abutment. Cantilever construction is less popular with beam-and-slab decks because large trusses are usually needed temporarily to provide



Fig. 1.15 Concrete box girder deck of segmental construction at East Moors Viaduct, Cardiff, Wales; designed by Robert Benaim & Associates. Photographs courtesy of Shepherd, Hill Ltd and Robert Benaim & Associates.

