CONCRETE BRIDGES:

DESIGN AND CONSTRUCTION

A C LIEBENBERG

CONCRETE DESIGN & CONSTRUCTION SERIES

Concrete Bridges: Design and Construction

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Preface

This book is an extended version of a chapter on 'Bridges' by the same author in the *Handbook of Structural Concrete* which was edited by F.K. Kong, R.H. Evans, E. Cohen and F. Roll and published by Pitman Books Limited of London and McGraw-Hill of New York in 1983. In addition to sections not previously included, it also contains various improvements and updates of the older text. It is intended as a reference work on the current state of the art and science of design and construction of concrete bridges to meet the needs of practising civil and structural engineers as well as students. However, it is not intended to be a comprehensive treatise on concrete bridges but rather a complementary work to other publications and codes of practice that deal more systematically with the details of practical design and construction. More emphasis is given to subject matter and concepts that are not always covered in textbooks but nevertheless are very important to the understanding of the design, construction and maintenance of concrete bridges. Reference is made to other chapters of the *Handbook of Structural Concrete* as well as other publications covering matters that have been omitted due to restrictions on length.

As knowledge of the past is essential in any field of endeavour this work commences with an historical summary of the development of the art of bridge building towards the numerous types and configurations of modern concrete bridges. The importance of the appreciation of aesthetics and the protection of the natural environment is emphasized. The need for an understanding of the underlying philosophy of the structural design process, including the nature of innovation and the concepts of risk, reliability and utility, is explained. The underlying thesis is that the final design product should in theory be optimized in terms of total utility, which includes all the relevant costs, benefits and damages to the immediate client, society in general and the natural environment over the life span of the bridge.

Relevant design criteria, such as the various actions and environmental effects on bridges, are defined and a summary given of suitable analytical

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procedures based on a range of mathematical modelling techniques and computer applications. Design and construction practices are described and the importance of field inspections and maintenance procedures emphasized. The causes and nature of the deterioration of concrete bridges are enumerated as well as methods of assessment of the damages. Effective repair or rehabilitation techniques are explained.

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Notation

A_{ef}	effective torsion area
A_{eq}	equivalent shear area
A_s	area of reinforcing steel
A_{sh}	shear area
a, b	diagonal and off-diagonal position indicators of the independent bending stiffness terms of the member matrix respectively
B	expected present value of the overall benefits derived from the existence of the structure (positive utility)
$\boldsymbol{C}$	constant damping matrix
C_i	initial cost
C_m	capitalized normal maintenance costs
C_p	capitalized prime costs $= (C_i + C_m)$
C_t	total capitalized costs (negative utility)
d_{ef}	diameter of largest circle within the boundaries of A_{ef}
E	Young's modulus or modulus of elasticity
E_c	initial tangent modulus of concrete
E_d	expectation of damages
E_{dyn}	dynamic modulus of elasticity
E_H	standard hydrogen potential
E_{long}	long-term modulus of elasticity
E_S	Young's modulus of steel
E_{sec}	secant modulus of concrete
E_t	time-dependent modulus of elasticity
e	eccentricity
F	force on a member; safety factor
$\boldsymbol{F}$	internal member stress resultant vector
F_R	probability distribution function of the structural capacity, R
F_x	equivalent static earthquake load
f	foundation factors used in conjunction with earthquake loading

$\boldsymbol{f}$	member fixed-end vector
f_S	probability density function of the load effect, S
G	shear modulus
g	acceleration due to gravity
h_{ef}	equivalent wall thickness used to define torsion stiffness
I	importance factor of structures used in conjunction with earthquake loading; moment of inertia or second moment of area of a section (sectional inertia)
I_d	effective sectional inertia for an applied deflection
I_{eq}	equivalent sectional inertia
I_r	effective sectional inertia for an applied rotation
J	torsional moment of inertia
$\boldsymbol{K}$	stiffness matrix
k	member stiffness
$\boldsymbol{k}$	member stiffness matrix
k_d	deflection stiffness in bending
k_{gh}	peak horizontal ground acceleration
k_r	rotational stiffness in bending
k_t	torsional stiffness
L	length of a member; design life in years; loaded length of bridge deck
L_w	wind-loaded length
M	bending moment; safety margin
$\boldsymbol{M}$	constant mass matrix
m	mass
m_M	mean safety margin
m_R	mean resistance
m_S	mean applied force
N	judgement factor
n	number of degrees of freedom in a structure; number of piles in a group
n_0	fundamental natural frequency
P	load or force
$P\Delta$	the bending moment increment due to column sway or drift
$\boldsymbol{p}$	stress resultant
p	probability of an event
p_f	probability of failure
p_m	probability of exceeding a serviceability limit state
p_n	probability of reaching an ultimate limit state
p_s	probability of survival
R	redistribution factor; resistance; structural capacity; reliability
$\boldsymbol{R}$	external nodal point load vector

R_D	resistance of a section for design purposes
r	minimum number of piles required to ensure statical equilibrium
S	applied force; load effect
S_D	force on a section for design purposes
S_a	the seismic response factor for a structure read from the response spectrum
S_m	capitalized cost of damage or loss due to non-compliance with serviceability criteria
s	stirrup spacing
T	return period; natural period of vibration
$\boldsymbol{T}$	transformation matrix
t	time
U_u	capitalized cost of reaching an ultimate limit state
$\boldsymbol{U}$	time-dependent displacement vector
$\dot{\boldsymbol{U}}$	time-dependent velocity vector
$\ddot{\boldsymbol{U}}$	time-dependent acceleration vector
u_{ef}	polygonal perimeter length of section in torsion
V	coefficient of variation
v	mean hourly wind speed
W	load
β	safety or reliability index
Δ	an increment
Δ_c	compression
γ_i	modal participation factor used for earthquake loading
δ	deflection of a member or support
η	relaxation coefficient of concrete
θ	rotation of a joint
λ	fixity factor used to determine member stiffness
μ	ductility factor of the structure; coefficient of friction
Π	product of
Σ	sum of
σ	variance
ϕ or ϕ_t	coefficient of creep of concrete to be used for long-term load effects
Φ	normal distribution function
Ψ_{ij}	normalized mode component of the ith mode in the direction of the jth degree of freedom
ω	radial frequency

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1 Introduction

1.1 General

In the following sections an account is given of the historical development of the art and science of bridge building from the primitive beginnings to the magnificent structures of today. There are many useful lessons to be learnt, not only from the progress through time but especially from the many failures. The importance of the parallel developments in mathematical analysis and the technologies of construction materials and techniques is very evident. It is also clear that at any time the available construction materials played a dominating role in determining the types and ranges of feasible and viable structures. This situation still pertains today; thus there is a place for a book devoted to concrete as the construction material which, in conjunction with steel as reinforcing, dominates the scene in many countries. This does not ignore the fact that many, including the biggest, bridges are still being built of steel and always will be of some metal alloy or other. It simply recognizes the fact that concrete bridges, whether ordinarily reinforced, prestressed or composite, are in a class distinct from that of structural steel, with very different design approaches, and accordingly they have become a specialized field. Nevertheless, the designer in concrete must have a substantial understanding of structural steel design codes and experience in the design of steel and timber structures because of their important applications in the form of temporary construction supports, launching girders and towers.

The continuing improvements in the quality and range of concretes as well as reinforcing steel and steel used in prestressing or in composite construction furthermore open challenging opportunities for the future applications of concrete. The evolution of large-span cable-suspended concrete bridges presents exciting possibilities and makes them potential competitors of longspan steel bridges of up to 700 m (2300 ft) clear span. However, the engineering profession, in applying concrete to such a wide range of applications over the years, often erred in not giving sufficient attention to all the details of construction and especially to the need for

continuing site inspections and maintenance of bridges which are essential to ensure a long life.

The general approach to design is based on ISO 2394, *General Principles for the Verification of the Safety of Structures*[1.1] as expounded in Volumes I and II of the *International System of Unified Standard Codes of Practice for Structures*[1.2] published by the Comité Euro-International du Béton (CEB) in 1978. This code has been revised and a First Draft of CEB–FIP Model Code 1990 — has been printed. As they are model codes, reference is also made to specific codes that are being applied in practice or are in the process of being introduced.

The units in this book are those of the SI (International System of Units), but, where it is useful, imperial dimensions are also given.

1.2 A Summary of the Historical Development of the Art and Science of Bridge Building

1.2.1 Ancient History

Bridges have fascinated mankind from the earliest recorded times. Apart from their civil and military importance, they are considered by many as symbolic of civil engineering achievement. Although the origins are uncertain, the evolution of the various types of bridge structures probably covers a period exceeding 5000 years. One can speculate with fair certainty that the bridge types that are described in the next section were foreshadowed in the earliest constructions to span rivers and gorges. These included the primitive use of timber logs or stone lintels as beams or slabs, stone clapper bridges, boulders in crude masonry arches and ropes made of creepers, vines or woven natural fibres in small suspension bridges. The subsequent development by empirical methods can clearly be related to the advancement of successive civilizations and their knowledge of materials of construction. Various authors have covered the major periods in the history of bridges in some detail[1.3–1.5] and made reference to source material dating back more than four millennia. The history of the development of bridges makes most interesting reading and an in-depth study of the above references is essential for any prospective bridge designer. Only a few salient developments are given here.

The earliest bridge on record was that built on the Nile by Menes, the first king of the Egyptians, about 2650 BC. No details of this bridge are known but a remarkable bridge, with a timber deck on stone piers as described by Diodorus Siculus, was built over the Euphrates in Babylon 4000 years ago. Primitive suspension bridges, where the traveller slid along a single cable made of strands of bamboo rope twisted together,

were made in India. The first true suspension bridge consisted of three cables: two on each side to act as handrails to enable the passenger to walk on the third, which was tied below. The oldest extant chain bridge is thought to be that over the river Tchin-tchin in China. India is noted for its early use of iron suspension chain bridges. Another form of primitive bridge in timber was a girder type on floating supports, which was the forerunner of the pontoon bridges used in modern warfare.

The development of the brick or masonry arch can be traced back to the Chaldeans and Assyrians but was apparently developed independently in the Western world. Until the time of the Roman conquest of Persia, it appears that these mostly took the form of corbelled arches with a pointed profile built of brick or stone in horizontal courses. These have been found widely distributed over various parts of the ancient world including China, the Middle East and Mexico. The first arches with voussoirs were most probably built in Egypt, where tombs dating from 1800 BC were discovered with roofs of elliptical profile. The Persians built arches with ogival or pointed as well as elliptical profiles. The Etruscans, the immediate predecessors of the Romans, developed the semicircular arch built with voussoirs. There is a difference of opinion amongst historians as to whether the Romans absorbed this knowledge during the Roman Conquest or learned about the arch directly from Eastern people. The Greeks had developed an elementary theory of statics and Archimedes (287–212 BC) understood the basic conditions of equilibirum. There is, however, no evidence from ruins that they built true stone arches. Even the Romans apparently never had a full understanding of how arches acted to resist the forces generated by the applied loads. However, they have gone down in history as the greatest builders of stone-masonry arches, almost without exception of circular profile and of comparatively small span and heavy proportions. From experience, observation and deduction within the limits of their understanding, they perfected the art of construction to the extent that many examples of their arches, such as the masterpiece of Agrippa, the Pont du Gard, 19 BC (Fig. 1.1), are to this day visible evidence of their creative engineering ability.

The Greeks and Romans used timber for less permanent structures. Timber trestle bridges were developed for military purposes. They built the first timber bridge across the Thames in London.

Perhaps the most important discovery of the Roman builders was that of natural cement, pozzolana, a volcanic sand found at Pozzuoli near Naples, that forms a hydraulic cement when mixed with ordinary lime and was the forerunner of modern concrete.

Bridge builders in those ancient times were practical men who unfortunately did not readily avail themselves of the ideas of philosophers, who were interested in the early developments of applied science. This

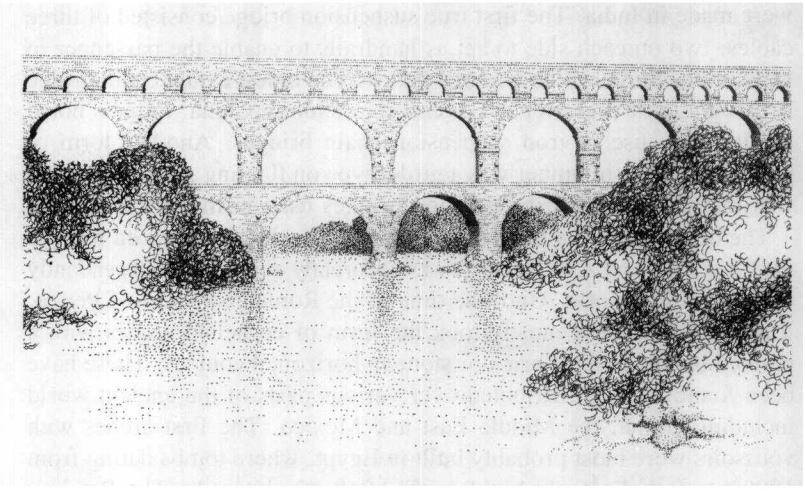

Figure 1.1 Pont du Gard — Agrippa's masterpiece, 19 BC (sketch based on photograph in Ref 1.6)

lack of communication delayed the proper understanding by bridge builders of the structures that they were developing by empirical methods, for many centuries.

1.2.2 The Middle Ages

A great deal of the knowledge of structural engineering accumulated by the Romans was lost during the Middle Ages, so that little progress was made and hardly any structural innovation took place. The art did, however, spread more widely throughout Europe. Chinese timber arch bridges built in the 10th century are still in use. How far the technical as distinct from empirical knowledge of bridge designers had developed by the end of this period is not known.

1.2.3 The Renaissance and the Age of Reason

The revival in the arts and sciences under the leadership of men such as Leonardo da Vinci (1452–1519) that occurred during the Renaissance had a fundamental influence on engineering and especially on bridge design. It heralded the birth of what can be considered to be the modern bridge in that it brought about a profound marriage between the conceptual understanding of structures based on theoretical considerations and the practice of bridge construction. This elevated bridge building to an applied science. Practical builders could no longer ignore the ideas of theoretical designers. Several of the great names associated with bridge building in the ensuing periods were to be men who combined both abilities.

The most notable bridges which were the earliest manifestation of this

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