Movable Bridge Design

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**Charles Birnstiel, William Bowden
and George A Foerster**

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NB: British English has been used throughout this book, but occasionally readers will find non-British terms where US case studies and examples have been cited.

Preface

This book is intended for those involved in design, engineering, construction and maintenance of movable bridges. It was brought together by authors with knowledge and experience gained from working on a broad range of movable bridge projects. Movable spans of many kinds are treated in the book, from short spans over narrow navigation channels to the 340 metre span of the two-armed swing bridge over the Suez Canal in Egypt. It deals with bridges supporting only a few pedestrians, those loaded by 32 tonne (72 kip) lorries, those with an average daily traffic (ADT) of 200 000 vehicles, and others with multiple railway tracks designed for a running load of 15 tonnes per metre (10 kips per foot) of track. Movable bridges are considered herein that are part of the city street fabric and railway bridges so isolated that the nearest roadway is 15 km (9 miles) away. Various forms of operating machinery and controls are discussed from the viewpoints of design, inspection, testing, and maintenance.

The primary purpose of this book is to serve as a reference on past and current mechanical, electrical, hydraulic, and structural design of movable bridges. The emphasis is on the machinery required to operate the movable spans and to stabilise them, in both the open and closed positions. Among the subjects included are a brief historical account of the development of movable bridges citing significant structures, typical superstructure forms, engineering design specifications and standards, construction materials including physical properties and kinds failure, span drive and stabilising machinery arrangements, and mechanical, hydraulic, electrical and structural design.

The reality is that thousands of movable bridges exist, many over 50 years old, and that they have deteriorated since they were built due to environmental effects, traffic overloads and inadequate maintenance. Funding for replacing deteriorated bridges is scarce in many jurisdictions and besides the permitting process for new construction on new alignments, with its required environmental impact statements, can take decades. If the condition of the bridge is poor, with respect to safety and operating reliability, the practical solution is often rehabilitation of the structure, machinery and controls. Widening of the carriageway may be a feature of the rehabilitation plans. The authors are cognisant of this situation and have endeavoured to present the development of the systems during the 20th century in minimal space. Current technology is an outgrowth of prior engineering.

It is presupposed that readers have knowledge of elementary physics. To appreciate the chapters on materials, and mechanical, hydraulic and electrical design, the reader having a background in statics and dynamics, strength of materials, structural analysis, fluid mechanics, and electrical circuits – as generally taught at a university undergraduate level – will have an advantage. Mechanical design is presented at an elementary level. Advanced solid mechanics topics are not stressed. The book considers a wide range of topics within an interdisciplinary subject and so, because of space limitations, some aspects are not treated comprehensively. However, in such cases reference is made to multiple publications that treat those topics in depth.

Acknowledgements

Thanks are due to the many persons who have contributed to this book in some way, especially William Bowden, the late Robert L Cragg, George A Foerster, James M Phillips III and Robert J Tosolt. Also thanks to the writers' families for forbearance during the manuscript preparation process.

The impetus for writing this book came two decades ago from the late Jerome SB Iffland, the President of Iffland Kavanagh Waterbury. Also recognised are the contributions of the late Alexander H McPhee who served as adviser on movable bridge machinery systems in the early 1980s when that technology was closely held by a few bridge engineering firms.

Thanks also to agencies that facilitated inspections of their movable bridge stock by assigning senior staff to arrange for and accompany Charles Birnstiel on bridge tours. Some of the agencies and personnel in the UK were:

- Kingston upon Hull City Council – Keith Stubs and Barrie Young.
- The Manchester Ship Canal Company – Ray Howells and David Ogilvie.
- Humber Bridge Board – Roger Evans.
- Port of Tyne Authority – Donald Graham and George Fenwick.
- Newport, Wales, City Council.
- Corporation of London – Charles Harrison in co-operation with Rexroth staff members Nigel Hart, Anneliese Herteux and Erich Wirzberger.

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Charles Birnstiel, May, 2015

About the authors

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Charles Birnstiel studied civil engineering at New York University in New York City, taking his bachelor's and master's degrees in 1954 and 1957, and earning his doctorate in 1962. His engineering experience includes 20 years of teaching and structural mechanics research at New York and Polytechnic universities and 23 years leading a multidisciplinary engineering firm specialising in the design, inspection and testing of movable bridge machinery, followed by employment with Hardesty and Hanover, LLC, a prominent movable bridge engineering firm headquartered in New York City.

Besides his structural stability research at university, Dr Birnstiel has been active on technical committees of the American Society of Civil Engineers (ASCE). He was chairman of the ASCE Standards Committee responsible for the ASCE/SEI 19-10 *Structural Applications of Steel Cables for Buildings* Standard. He is an emeritus member of the American Railway Engineering and Maintenance-of-Way Association (AREMA) Committee 15 – Bridges, and participated for many years in updating the AREMA *Manual for Railway Engineering* – a recommended practice. He is a licensed professional engineer in several US states and a Fellow of the Institution of Civil Engineers (FICE) and of ASCE.

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William Bowden is the founder and president of Link Control Systems, a firm that has been in the movable bridge industry for 35 years and is a recognised leader in the field. William Bowden has been involved with the design and supervision of bridge control systems during this time and has completed over 200 movable bridge control systems. He has also taught classes on control system design and maintenance for the Institute of Electrical and Electronic Engineers and has presented technical papers covering various aspects of bridge control system design. William holds a Master of Science degree from Fordham University and two Master of Arts degrees from the Seminary of the Immaculate Conception.

George A Foerster

George A Foerster is an associate senior mechanical engineer in the New York City office of engineering firm Hardesty and Hanover, LLC, which specialises in bridge design and inspection. George graduated from the State University of New York at Stony Brook, NY, in 1991, with a Bachelor of Engineering degree, majoring in mechanical engineering. Since college, George has accumulated over 22 years' experience in the design, condition inspection and construction inspection of machinery for movable bridges and heavy movable structures. As a senior mechanical engineer George is involved with technical concept development, design development, specifications, cost estimating, analysis, inspections, condition reports, construction inspection reports, emergency response, and proposed repairs. Project experience includes all major movable bridge types, ferry transfer bridges, movable inspection platforms and movable stadium roofs. In the USA, George is a licensed professional engineer in several states and in

Washington, DC. He is a member of Heavy Movable Structures (HMS) and the American Society of Highway Engineers (ASHE). He has presented several HMS papers on topics involving movable bridges and the mechanical components and systems associated with them.

About the contributors

Robert L Cragg

The late Robert L Cragg received a Bachelor of Science degree in mechanical engineering from Drexel Institute of Technology in 1947 after military service in World War II, including the Battle of the Bulge. He received the Bronze Star Medal for bravery and was named *Chevalier* of the *Légion d'honneur* for his service in the liberation of France. After graduation he associated himself with the rolling element bearing manufacturers in the Philadelphia, PA area and eventually joined Earle Gear and Machine Co., in Philadelphia. He was Vice President of Earle when that firm was acquired by Steward Machine Co. of Birmingham, AL, in 1985. Until December 2012 he remained an active consultant to Steward. He authored manuals on movable bridge inspections and related topics and participated in conducting movable bridge inspectors' maintenance training schools. The energy-absorbing span lock system now marketed by Steward was patented by Cragg. Cragg was a licensed professional engineer in several states. Until his passing on 16 January 2013 he was a respected member of the movable bridge engineering profession.

James M Phillips III

James M Phillips III is a bridge practice leader for Hardesty and Hanover, LLC, in Tampa, FL. His career includes more than 32 years of experience in movable bridge inspection, planning, design and construction engineering with leading consulting engineering firms such as Parsons Brinckerhoff, EC Driver and Associates, and URS. James has participated in the planning and design of dozens of new movable bridge projects throughout the USA as well as internationally. In 1982 he earned a Bachelor of Science degree in civil engineering from the University of Florida, College of Engineering. He is a licensed professional engineer in many states. In addition to his formal education in civil engineering, he has more than 32 years of practical experience in design of movable bridge mechanical and hydraulic systems and is certified by the Fluid Power Society as both a fluid power specialist and a fluid power engineer. In addition to movable bridges, James's experience includes design of machinery and fluid power drives for navigation locks, flood control gates, and other large movable structures. He has been responsible for design of hydraulic drives of numerous configurations, including open loop hydraulic motor drives, open loop hydraulic cylinder drives, closed loop hydraulic motor drives, variable displacement pump control, flux-vector pump control, proportional valve flow control and others.

Robert J Tosolt

Robert J (Bob) Tosolt is a practising professional engineer with over 23 years of experience working with mechanical operating and support systems on all types and vintages of movable bridges. He received a Bachelor of Science degree in mechanical engineering from Lafayette College, Easton, PA in 1992. He gained his initial employment under Charles Birnstiel from 1992 to 1995 and has since been employed at Stafford Bandlow Engineering, Inc. in Doylestown, PA, where he now serves as senior engineer and associate. Robert has been responsible for new machinery design for bascule, swing,

and vertical lift bridge projects, and has extensive practical experience that has been gained through field services (including inspection, construction support, installation acceptance, operational testing and troubleshooting, machinery start-up testing, emergency call-out, and failure analyses). He is a licensed professional engineer in 11 states, and is an active member of AREMA and HMS.

Notation

SYMBOLGY

Latin letters

A_b	hydraulic cylinder bore area (in. ²); keyway bearing area
$A_{\text{effective}}$	effective metal cross-sectional area of wire rope
A_r	hydraulic cylinder rod end area
A_s	key shear area
B/L	gearset backlash (in.)
C	compressive force; gearset centre distance (in.); degree Centigrade
C_D	size factor
C_H	hardness ratio factor
C_M	miscellaneous factor
C_R	reliability factor
C_S	surface roughness factor
C_T	temperature factor
$C_{\text{basic rating}}$	bearing basic load rating
C_d	orifice coefficient
C_f	surface condition factor for pitting resistance
C_p	elastic coefficient for steel
c	bolt torque coefficient, also known as the bolt 'K factor'
D	diameter of curved surface; shaft diameter; gear pitch diameter (in.); sheave diameter
D_{ed}	gear tooth dedendum (in.)
D_b	diameter of cylinder bore (in.)
D_o	diameter of an orifice (in.)
D_r	diameter of cylinder rod (in.)
D_{tread}	tread diameter of sheave grooves
d_w	diameter of outer wire
d	diameter, shaft diameter; diameter of roller; nominal bolt diameter; displacement of a pump or motor (in. ³ /rev); pinion pitch diameter (in.); rope diameter
E	modulus of elasticity, psi (taken as 29×10^6 psi for steel)
E_s	secant modulus of elasticity
E_w	tensile modulus of elasticity of steel wire
Eff	power transmission efficiency
F	force (lb); specified dwell; tooth net face width (in.); degree Fahrenheit
FS	factor of safety
F_1	test force
F_E	Euler bucking load (lb)
F_a	applied axial load
F_b	design buckling load for a hydraulic cylinder (lb)
F_i	bolt initial preload
F_o	preliminary test force
F_r	applied radial load
F_y	minimum material yield strength
f	AREMA shaft extreme fibre stress, tension or compression; distance between P and assumed cantilevered beam point of fixity
f.c.c.	face-centred cubic crystal structure
F	tooth net face width (in.)

g	acceleration due to gravity; distance to shear lock from assumed cantilevered beam point of fixity
I	geometry factor for pitting resistance
J	geometry factor for bending strength
K	effective length factor for buckling (unitless); impact factor
K_B	rim thickness factor
K_F	fatigue stress concentration for normal stress
K_{FS}	fatigue stress concentration for shear stress
K_R	reliability factor
K_S	tooth size factor
K_T	temperature factor
K_V	dynamic factor
K_{bolt}	bolt 'K factor'
K_f	stress correction factor
K_m	load distribution factor
K_{my}	load distribution factor for overload condition
K_o	overload factor
K_t	theoretical stress concentration factor for normal stress
K_{ts}	theoretical stress concentration factor for shear stress
K_y	yield strength factor
L	length; bearing journal length; length of hub-bearing surface
$L_{\text{allowable}}$	allowable length of shaft
L_{10}	anti-friction bearing life in hours
ℓ	distance from mid-span to trunnion axis
M	bending moment
M_b	moment necessary to move the leaf solely to overcome imbalance
m	mass; distance from front live load support to trunnion access
m_G	gear ratio
N_G	number of teeth in the gear
N_P	number of teeth in the pinion
n	number of teeth; shaft speed (rpm); rotational speed (rpm)
n_c	critical shaft speed (rpm)
n_i	load modifier
P	concentrated live load; direct load on wire rope; pressure (psi)
PA	pressure angle (degree)
P_b	pressure acting on the blind end of a cylinder piston (psi)
P_c	circular pitch (in.); shrink-fit pressure
$P_{\text{equivalent}}$	equivalent load on bearing
P_{hp}	horsepower
P_{nd}	normal diametrical pitch (in.)
P_o	operating load
P_r	pressure acting on the rod end of a cylinder piston (psi)
p	circular pitch (in.)
p_d	pitch diameter
Q	flow (gpm)
Q_i	force effect
q	fatigue design notch sensitivity factor
R	nominal outside radius of inner member; radius of roll
R_n	nominal resistance
R_r	factored resistance
r	disk-projected bearing radius; radius of shaft at friction surface

r_b	radius to centre of keyway bearing area
r_i	inside radius of inner member
r_o	outside radius of outer member
r_s	radius at shear plane
S	AREMA shaft shear stress; shear force transmitted by lock; specific gravity of hydraulic fluid
S_F	bending safety factor
S_H	pitting safety factor
S_{ac}	allowable contract stress (psi)
S_{at}	allowable bending stress (psi)
S_{ay}	allowable yield stress (psi)
s	distance from point on bascule leaf to centre of rotation; permissible unit stress (psi)
T	tensile force; torque (in.-lb); full design torque load (in.-lb); torsional moment
T_i	input torque (in.-lb)
T_o	output torque (in.-lb)
T_r	recrystallisation temperature
t	distance of roll; holding time (hours)
V	rotation factor; velocity of pitch circle (ft/min)
v	cylinder rod velocity (in./sec)
W	allowable tooth load (lb); ball indenter force; weight
WD	tooth whole depth (in.)
W_{max}	maximum factored resistance (lb)
W_t	transmitted tangential load (lb)
W_{tac}	factored surface durability resistance (lb)
W_{tat}	factored flexural resistance (lb)
w	angular velocity (rad/sec)
X	radial load factor
Y	thrust load factor
Y_N	stress cycle factor for bending strength
Y_i	load factor
y	tooth form factor
Z_N	stress cycle factor for pitting resistance

Greek letters

α	endurance limit factor
Δ_{DJ}	end clearance at diaphragm of mid-span lock for double-leaf rolling bascule
Δh_R	recession of point on rolling bascule leaf during rotation
Δh_T	recession of point on fixed trunnion bascule leaf during rotation
ΔP	differential pressure; pressure drop across a component; branch of a circuit (psi)
δ	radial interference (distance)
η_m	efficiency, mechanical (unitless)
η_o	efficiency, overall (unitless)
η_v	efficiency, volumetric (unitless)
θ	opening angle of bascule leaf measured from horizontal (degrees)
θ_m	maximum opening angle (degrees)
μ	friction coefficient
σ	maximum computed combined bending or bearing stress

σ_a	amplitude normal stress
σ'_a	von Mises applied amplitude stress
$\sigma_{\text{allowable}}$	allowable combined, bending or bearing stress
σ_b	maximum bending stress in wire rope
σ_{brg}	bearing stress
$\sigma_{\text{direct load}}$	stress on wire rope due to direct load (based on AASHTO equation)
σ_e	endurance limit
σ_m	mean normal stress
σ'_m	von Mises applied mean stress
σ_{max}	maximum applied normal stress
σ_{min}	minimum applied normal stress
σ_t	total stress in wire rope
σ_{ut}	ultimate strength
σ_{yt}	yield strength
τ	maximum computed shear stress
τ_a	amplitude shear stress
$\tau_{\text{allowable}}$	allowable shear stress
τ_m	mean shear stress
τ_{max}	maximum applied shear stress
τ_{min}	minimum applied shear stress
ϕ	resistance factor
ω	angular velocity

Abbreviations and terminology

A_1	lower critical temperature
A_2	Curie point
A_3	upper critical temperature with $C \leq 0.77\%$
A_4	arrest at which iron transforms from b.c.c. to f.c.c.
A_{cm}	upper critical temperature with $C > 0.77\%$
AASHTO	American Association of State Highway and Transportation Officials
Add	gear tooth addendum (in.)
ADT	average daily traffic
ADTT	average daily truck traffic
AFD	adjustable frequency drive
AGMA	American Gear Manufacturers' Association
AISI	American Iron and Steel Institute
ANSI	American National Standards Institute
ASM	American Society for Metals
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASCE	American Society of Civil Engineers
ASD	allowable stress design
ASTM	American Society for Testing and Materials
AWPA	American Wood-Preservers Association
C	element carbon
CCTV	closed circuit television
b.c.c.	body-centred cubic crystal structure
b.c.t.	body-centred tetragonal crystal structure
CDA	Copper Development Association

Cr	element chromium
CS	constructional stretch
DIN	German Institute for Standardisation
DF	design factor
EEIP	extra extra improved plow steel
EIP	extra improved plow steel
EN	European standard
Fe	element iron
FEA	finite element analysis
FEM	Fédération Européene de la Manutention
FHWA	Federal Highway Administration
FLT	full load torque
FRP	fibre reinforced polymer/plastic
FVD	flux vector drives
H	element hydrogen
HGE	hydrogen gas embrittlement
HMI	human machine interface
hp	horsepower
HR	Rockwell hardness number
HRC	hardness on the Rockwell C scale made with a diamond indenter
HVOF	high-velocity oxygen fuel
IPS	improved plow steel
ISO	International Organisation for Standardisation
IWRC	independent wire rope core
LR	lubrication regimes
LRFD	load and resistance factor design
LSHT	low-speed-high-torque
LVDT	linear visible differential transformer
MBF	minimum breaking force
MDS	molybdenum disulphide
Mo	element molybdeum
Mn	element manganese
ND	neutron diffraction
NEMA	National Electrical Manufacturers' Association
NEN	Nederlands Normalistie Instituut (Netherlands Standardisation Institute) movable bridge specification
NFPA	National Fluid Power Association
Ni	element nickel
O	element oxygen
OSD	orthotropic steel deck
PDI	process derivative – integral
PID	proportional–integral–derivative
PLC	programmable logic controller
PTA	plasma transfer arc
PTFE	polytetrafluorethylene
RPM	revolutions per minute
SAE	Society of Automotive Engineers
SCC	stress-corrosion cracking
Si	element silicon
S–N curve	stress–life curve (plot of alternating stress against cycles to failure); Wöhler diagram

TWI	The Welding Institute
UPS	uninterruptible power supply
USCU	US customary units
V	element vanadium
VSR	vibratory stress relief
W	element tungsten
WSC	independent strand core
WSD	working stress design
XRD	x-ray diffraction