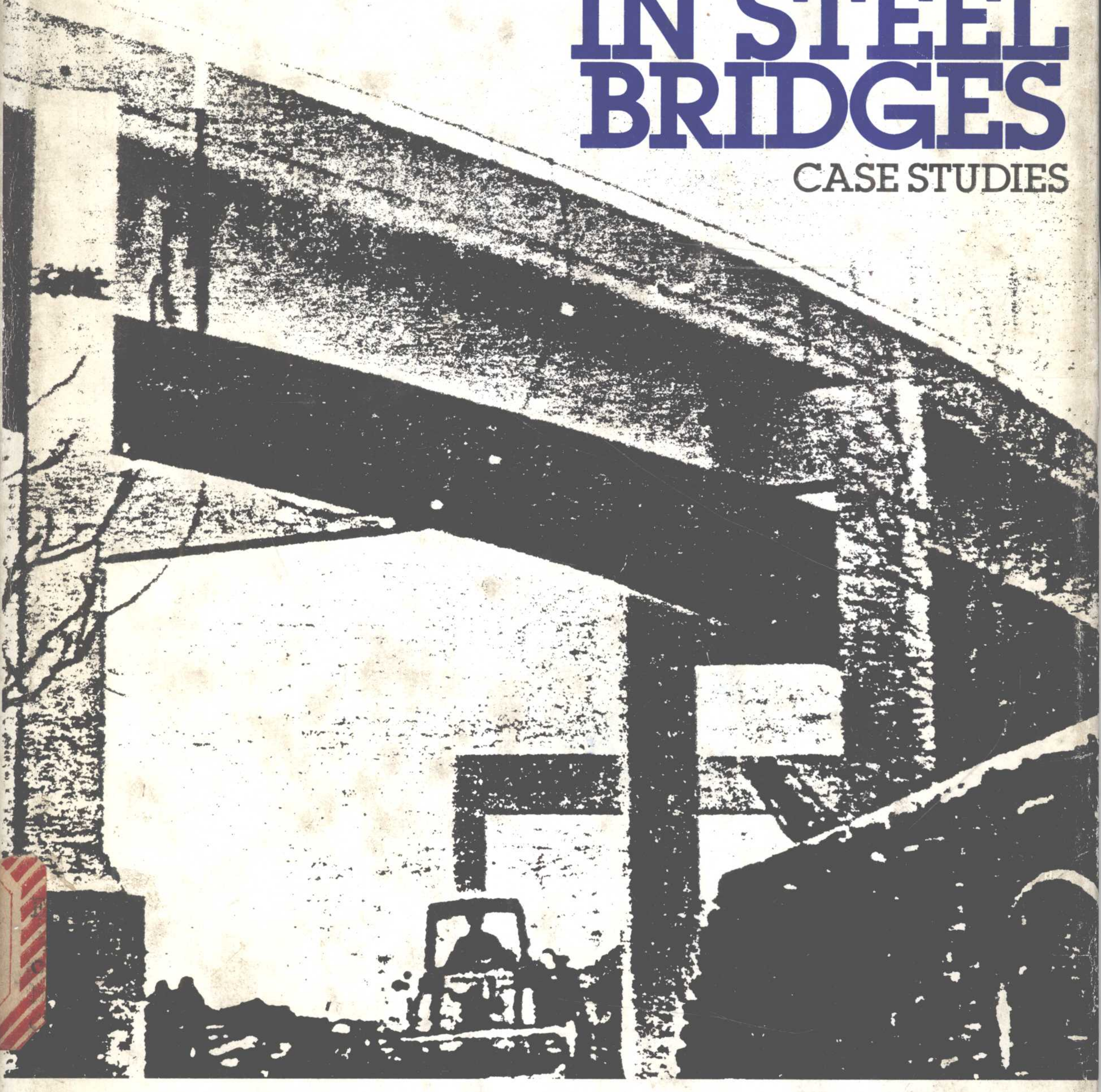
FATIGUE AND FRACTURE IN STEEL BRIDGES

CASE STUDIES



JOHN W. FISHER

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A WILEY-INTERSCIENCE PUBLICATION

JOHN WILEY & SONS

New York · Chichester · Brisbane · Toronto · Singapore

Library of Congress Cataloging in Publication Data:

Fisher, John W., 1931–
Fatigue and fracture in steel bridges.
"A Wiley-Interscience publication."
Includes index.
1. Bridges, Iron and steel. 2. Steel, Structural—Fatigue. 3. Steel, Structural—Fracture. I. Title.
TG380.F57 1984 624'.252 83-23495
ISBN 0-471-80469-X

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Preface

Since 1967 a number of highway and railroad bridge structures in the United States and Canada have experienced fatigue cracking which sometimes resulted in brittle fracture as a result of service loading. This book provides a detailed review and summary of 22 case studies of bridges that have experienced crack growth.

My objective in preparing this book is to make the reader aware of the many types of cracks that have developed in bridge structures under service loads, examine the reasons for their occurrence, and provide a fracture mechanics evaluation in order to relate the parameters of crack size, stress, detail geometry, crack propagation, and material toughness. The individual cases provide valuable insight into the causes of cracking, the significance of details, and the significance of defects on the performance of cyclic loaded structures. All of the causes of cracking discussed in this book can be prevented with the engineering knowledge and other tools available today. The lessons learned from the past should assist with an understanding of the behavior of structures and the importance of detail and execution. They assist toward the objective of enhanced reliability for structural systems subjected to cyclic loads.

The book is divided into two parts. The first deals with cracks that have formed as a result of low fatigue resistant details or large initial discontinuities. The large discontinuities often resulted because attachments were not considered as important as a groove welded tension flange. The welded joints that were used did not have adequate quality control requirements imposed on the welded joints. In several cases the structural detail created a cracklike geometric condition that was not recognized.

The second part of the book deals with fatigue cracks that form as a result of unanticipated secondary or displacement-induced stresses. These cases of cracking have developed in many types of structures with great frequency. They have generally formed in small web gaps between attachments and the girder flanges. The interaction between the main longitudinal members and the transverse framing such as cross-frames, diaphragms, and floor beams has resulted in out-of-plane distortion in the web gap that was not anticipated. Out-of-plane distortion has developed from handling and shipping of individual members, as well as the interaction between intersecting elements under everyday traffic. A large number of fatigue cracks generally form in a given structure because many small gaps normally exist.

Acknowledgment is due the U.S. Department of Transportation Federal Highway Administration for sponsoring a survey of localized failures due to cracking. A number of the examples given in this book resulted from information acquired during that study. Other cases were acquired over the years as a result of studies and evaluations that were carried out to determine the causes of cracking and to provide recommendations for the repair and retrofit of the damaged structure.

I am also indebted to the following individuals and organizations for their support and assistance on a variety of cases: C. F. Scheffey, C. F. Galambos, J. Nishanian, B. Brakke, and F. D. Sears—Federal Highway Administration; R. E. Cassano—California Department of Transportation; L. Koncza—Chicago Bridge Department; R. A. Norton and J. Cavanaugh—Connecticut Department of Transportation; C. E. Thunman—Illinois Department of Transportation; C. Pestotnic—Iowa Department of Transportation; L. Garrido—Louisiana Department of Transportation; D. Carpenter—Maryland Department of Transportation; K. V. Benthin—Minnesota Department of Highways; W. Sunderland—New Jersey Department of Transportation; R. B. Pfeifer—Ohio Department of Transportation; W. S. Hart—Oregon Department of Transportation; B. F. Kotalik—Pennsylvania Department of Transportation; K. C. Wilson—South Dakota Department of Transportation; W. Henneberger—Texas Department of Transportation; S. Gloyd—Washington Department of Transportation; W. A. Kline and S. Wood—Wisconsin Department of Transportation; P. F. Csagoly and A. Radkowski—Ontario Ministry of Transportation and Communications; Z. L. Szeliski and R. A. P. Sweeney—Canadian National Railroad; Delaware River Port Authority; Ammann and Whitney; DeLeuw-Cather; H. W. Lockner Inc.; Modjeski and Masters; Richardson Gordon and Associates and Wiss, Janney, Elstner and Associates.

Special thanks are due my colleagues Professors G. R. Irwin, A. W. Pense, R. Roberts, and B. T. Yen for their suggestions and assistance on a number of the case studies. Thanks are also due K. H. Frank, H. Hausammann, H. T. Sutherland, and D. R. Mertz for their assistance and help with a number of these studies.

The final manuscript was prepared while I was a Visiting Professor at the Institut de la Construction Métallique (ICOM), École Polytechnique Fédérale de Lausanne, Switzerland. I am particularly indebted to Professor J. C. Badoux for his support and assistance. The manuscript was in part typed at ICOM and in part by my secretary, Ruth Grimes, at Lehigh University. I appreciate the care and exactness that was taken. Thanks are also due R. N. Sopko, photographer at Fritz Engineering Laboratory, for the many photographs that are included in this book. I am also in-

debted to those who provided original prints of previously published photographs.

I am also grateful for the understanding and support provided by my wife, Nelda, and my children, J. Timothy, Christopher, Elizabeth, and Nevan, while I worked on this project.

JOHN W. FISHER

Bethlehem, Pennsylvania
March 1984

Abbreviations and Symbols

ABBREVIATIONS

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average daily vehicle traffic
ADTT	Average daily truck traffic
AISC	American Institute of Steel Construction
AREA	American Railway Engineering Association
ASTM	American Society for Testing and Materials
CVN	Charpy V-notch impact test, or pendulum energy loss measured in that test

SYMBOLS

A	Proportionality factor in relationship between cycles, N, and stress range
a	Half-length of a central (through-the-thickness) crack, length of an edge (through-the-thickness) crack, depth of a surface crack
$\frac{a}{c}$	Depth to surface-half-length ratio for a surface crack with the crack front shape approximated as half of an ellipse
C	Proportionality factor in relationship between fatigue crack growth rate and ΔK^n
c	Surface half-length of a surface crack
D	Weld leg size
$\frac{da}{dN}$	Fatigue crack growth rate

$E(k)$	Elliptical integral $= \int_0^{\pi/2} (1 - k^2 \cos u)^{1/2}\, du$ where $k = 1 - (a/c)^2$
$F_{(i)}$	Correction factors on $\sigma\sqrt{\pi a}$ to assist K value estimates
F_e	Related to a/c ratio for half elliptical shape
F_g	Related to stress gradient across the plane of the crack
F_s	Related to the free surface influence for a surface crack
F_w	Related to finite plate width relative to crack depth or crack length
H	Weld leg size
K	Stress intensity factor
K_c	Generic symbol for estimate of the opening mode K near the onset of rapid crack extension. For bridge steels, unless otherwise stated, the loading time is approximately one second.
K_{Ic}	Value of K_c for crack front stress state corresponding nearly to plane-strain
K_{Id}	Value of K_{Ic} for impact loading (a loading time less than 2 msec)
K_Q	An estimate of K_c or K_{Ic} from a fracture test in which allowance must be made for plastic yielding of the net section
ΔK	Maximum K value minus the minimum K value during a stress fluctuation
K_{tm} (or SCF)	Stress concentration factor, for example, at a notch root due to weldment contour
L	Length of web gap
l	Distance between point load and point on crack tip
M	Bending moment
N (or N_T)	Total number of fatigue cycles
N_i	Number of cycles corresponding to fatigue strength at stress range level S_{ri}
n_i	Number of cycles experienced at stress range level S_{ri}
n	Exponent for the crack growth relationship and for the stress range–cycle life relationship
P_{rs}	Point load residual stress force equal to product $\sigma_{rs} \cdot dA$
r_y	Plastic zone size radius
S_r	Stress range equal to the maximum stress minus the minimum stress during a stress fluctuation

S_r^D	Design stress range
S_{ri}	Stress range level i
$S_{r\text{Miner}}$	Effective stress range, calculated using Miner's rule and used to estimate effective ΔK values for variable amplitude loading
T	Temperature
T_s (or T-shift)	Estimated temperature shift of K_{Ic} versus T due to change of loading time
t	Thickness
t_{cp}	Cover plate thickness
t_f	Flange thickness
t_w	Web plate thickness
t_w'	Effective web plate thickness
t_p	Plate thickness for load-carrying cruciform joint
α	Reduction factor to correct for differences in calculated and measured stress
α_i	Frequency of occurrence of cyclic stress at stress range level S_{ri}, equal to n_i/N_T
Δ	Relative out-of-plane deflection in web gap
δ	Relative deflection between adjacent beams
θ	Rotation
ϕ	Angle between the major axis of an elliptical-shaped crack and a point on the crack front
ϕ_i	Ratio of gross vehicle weight GVW_i to design vehicle weight
σ	The nominal tensile fiber (or section) stress as commonly used for design purposes
σ_{rs}	Residual stress from welding
σ_Y	Tensile yield strength
$\Delta\sigma$	Cyclic stress range equal to S_r

Contents

PART II SECONDARY STRESSES AND DISTORTION-INDUCED STRESS

CHAPTER 1

Introduction

1.1 GENERAL OVERVIEW

Over the past two decades a number of localized failures developed in components of steel bridges, due to fatigue and brittle fracture. Where there were rapid cleavage separations, these were with few exceptions preceded by fatigue crack propagation on the crack surface. A survey [1.1] carried out between 1978 and 1981 including about 20 states and Ontario, Canada, amassed information on cracking that had developed at 142 bridge sites. Often several types of cracking were found at a single site, occurring in different details of a structure.

Table 1.1 provides a summary of the types of design details, identified by member or type of connection, at which cracks have developed in steel bridges. Listed in Column 2 are descriptions of the cracking. Twenty-eight general categories of cracking appear. This column indicates whether or not a large defect initiated the cracking or identifies the critical design condition. Often more than one factor contributed to the cracking, and each is identified. Column 3 gives the number of bridge sites at which the identified condition and cracking had developed. Usually there was more than one bridge at a given site. The last column provides the specification detail classification if no other unusual condition was observed. The classification system referred to here is one in general use in the various specifications of U.S. engineering associations such as the AASHTO Bridge Specification, the AREA Specifications for Steel Railway Bridges, and the AISC Specification for Steel Buildings. Where applicable a preexisting crack or an out-of-plane distortion that led to fatigue is indicated instead. Large cracks and distortion-induced cracking provide conditions that are not accounted for by the design provisions.

Table 1.1 shows that at least 60 bridge sites developed fatigue cracks as a result of out-of-plane distortion in a small gap. Most often this in-

Table 1.1 Summary of Types of Details Experiencing Cracking

Detail	Initial Defect or Condition	Number of Bridges	Fatigue Category
1. Eyebars	Stress corrosion	1	
	Forge laps, unknown defects	12	Initial crack
2. Pin plates	Frozen pins	1	Out of plane
	Other	1	D
3. Cover-plated beams	Normal weld toe	3	E'
	Fabrication cracks	1	$<E'$
4. Flange gussets	Welds toe	5	E or E'
5. Flange or web groove	Lack of fusion	6	Large initial crack
6. Coverplate groove	Lack of fusion	4	Large initial crack
7. Electroslag welds	Various flaws	6	
8. Longitudinal stiffeners	Lack of fusion, poor weld	4	Large initial crack
9. Web gusset	Intersecting welds	5	$<E'$
	Gap between stiffener and gusset	2	Out of plane
10. Flanges and brackets through web	Flange tip crack	3	$<E'$
11. Welded holes	Lack of fusion	3	Large initial cracks
12. Cantilever brackets	Tack welds	1	Out of plane
	Riveted connection	2	Out of plane
13. Lamellar tearing	Restraint	1	
14. Transverse stiffeners	Shipping and handling	4	Out of plane
15. Floor-beam connection plates	Web gaps	26	Out of plane
16. Diaphragm connection plates	Web gaps	9	Out of plane
17. Diaphragm and floor-beam connection plates at piers	Web gaps	4	Restraint
18. Tied arch floor beams	Web gaps	8	Out of plane
19. Tied arch floor-beam connection	Weld root	2	Restraint
20. Coped members	Flame-cut notch	13	Restraint
21. Welded web inserts	Lack of fusion	1	Large initial crack
22. Plug welds	Crack	1	Large initial crack
23. Gusset plates	Lateral bracing vibration	3	Out of plane