306

NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT

306

CORRELATION OF BRIDGE LOAD CAPACITY ESTIMATES WITH TEST DATA

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August 15, 1988

TO: CHIEF ADMINISTRATIVE OFFICERS
STATE HIGHWAY AND TRANSPORTATION DEPARTMENTS

SUBJECT: National Cooperative Highway Research Program Report 306, "Correlation of Bridge Load Capacity Estimates with Test Data" the Final Report on Project 12-28(8) of the FY '86 Program

I am enclosing one copy of the final report resulting from research administered by the National Cooperative Highway Research Program. The research was conducted by the University of Tennessee, Knoxville, Tennessee. In accordance with the selective distribution system of the Transportation Research Board, all persons who have selected the transportation modes and subject areas listed below will receive copies of this document.

The NCHRP staff has provided a foreword that succinctly summarizes the scope of the work and indicates the personnel who will find the results of particular interest. This will aid in the distribution of the report within your department and in practical application of the research findings. These findings add substantially to the body of knowledge concerning aspects of bridge behavior that are not normally considered during bridge evaluation and rating but which may be important in estimating the actual load capacity of a bridge. The report provides a summary and evaluation of more than 50 years of bridge load test data. The research attempted to isolate specific mechanisms through which bridges resist loads in ways other than those assumed during typical bridge design or evaluation. These aspects of bridge behavior are identified in the report by bridge type, providing guidance to the bridge engineer faced with the problem of improving the results of an analytical bridge evaluation.

Mode(s)	Area(s)
Highway transportation Public transit Rail transportation	Structures Design and Performance

Sincerely,

Thomas B. Deen
Executive Director

Enclosure

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 306

CORRELATION OF BRIDGE LOAD CAPACITY ESTIMATES WITH TEST DATA

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The University of Tennessee
Knoxville, Tennessee

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:

Structures Design and Performance
(Highway Transportation, Public Transit, Rail Transportation)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. JUNE 1988

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 306

Project 12-28(8) FY '86

ISSN 0077-5614

ISBN 0-309-04603-3

L. C. Catalog Card No. 88-50412

Price $11.20

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

FOREWORD

By Staff
Transportation
Research Board

This report contains the findings of a study that was performed to identify and evaluate aspects of bridge behavior that are not normally considered during bridge evaluation and rating but which may be important in estimating the actual load capacity of a bridge. More than 50 years of bridge test data were collected and evaluated in an attempt to isolate specific mechanisms through which bridges resist loads in ways other than those assumed during typical bridge design or evaluation. These aspects of bridge behavior are identified in the report by bridge type, providing guidance to the bridge engineer faced with the problem of improving the results of an analytical bridge evaluation. The report also includes a comprehensive annotated bibliography on bridge testing and test data. The contents of this report will be of immediate interest and use to bridge engineers, researchers, and others concerned with the load capacity evaluation of existing bridges.

A great deal of knowledge has been gained by physical testing of bridges and their components, much of it indicating that bridges resist loads in ways not always considered in bridge design or evaluation. Some causes of these differences in behavior may be: unintended composite action, wheel load distributions other than those assumed in design, participation of elements such as parapets and railings, participation of bracing and secondary members, and unintended continuity. More realistic modeling of the behavior of existing structures may make it possible to better evaluate the load capacity of the structure. With such refinements in structural modeling, more bridges may be allowed to continue in service and provide adequate load capacity or require only minor modifications or repairs.

NCHRP Project 12-28(8), "Improving Bridge Load Capacity Estimates by Correlation with Test Data," was initiated with the objective of assembling domestic and foreign bridge test data in order to identify, quantify, and report on significant aspects of observed behavior that are now not considered during bridge evaluation and rating. This analytical study was performed at the University of Tennessee.

The report summarizes the findings from that study. Numerous variables that might affect bridge behavior were identified and evaluated. The most significant variables found to affect behavior are presented in the report by bridge type, providing easy reference for the bridge engineer looking for guidance on methods to improve a structure's load capacity rating.

Several potential sources of unaccounted for load capacity are identified and discussed in detail. These sources include the effects of unintended composite action, unintended continuity, skew, and lateral load distribution. In order to quantify the effects of unintended composite action and unintended continuity for a specific bridge, however, some level of bridge load testing will most likely be required. In order to quantify the effects of skew and lateral load distribution for a specific bridge, additional analytical effort may be required.

The report also includes a comprehensive annotated bibliography on bridge load capacity tests performed between 1929 and 1987. Test reports on both full-scale structures and structural models are summarized in the bibliography.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 12-28(8) by personnel associated with the Department of Civil Engineering at The University of Tennessee, Knoxville. Edwin G. Burdette, Professor of Civil Engineering, was Principal Investigator, and David W. Goodpasture, Professor of Civil Engineering, was Co-Principal Investigator.

Most of the writing included in the body of this report was done by Drs. Burdette and Goodpasture. Dr. J. Harold Deatherage, former doctoral student who was responsible for much of the work described in the Interim Report, wrote the portion on load distribution case studies included in Appendix C. Satriya Suetoh, a masters degree candidate in Civil Engineering, wrote the portions on unintended composite action and effects of deterioration included in Appendixes D and E, respectively; and he was primarily responsible for the final format and presentation of the annotated bibliography. Gregory Tucker, another student in the masters degree program, contributed significantly to the portion in Chapter Two on effects of skew. Mr. Akif Ozbek, former masters student, was responsible for the load-deflection curves in Appendix A.

CORRELATION OF BRIDGE LOAD CAPACITY ESTIMATES WITH TEST DATA

SUMMARY

This report presents the results of a research effort, conducted under NCHRP Project 12-28(8), to assemble, review, and evaluate all available test data relating to the load capacity of highway bridges. The primary objective of the research was to identify and evaluate aspects of bridge behavior that are not normally considered in load capacity estimates but which may be important in enhancing the actual load capacity of a bridge.

The identification and brief summary of a large number of reference articles, relating to bridge load capacity and presented in the annotated bibliography in Appendix B of this final report, constitutes an important part of the findings of this research project.

The annotated bibliography presented in Appendix B includes research performed between 1929 and 1987. A broad spectrum of bridge types is considered. Special emphasis has been given to literature reporting a comparison between test data and analytical approaches. Information about tests on full size structures was obtained but only a few bridges have been tested to the inelastic region. Tests of models were of interest, but only results from models of the bridge, not tests on components, were examined in detail. Tests on single girders or other portions of the bridge were normally not included in the bibliography. Details of the test results were obtained from the publications and, in certain cases, the authors of the reports were contacted by phone to further investigate details not clearly described in the publication. The effects of assumptions in the analyses were examined, and independent calculations were performed to aid the researchers' understanding of the problems associated with the comparisons of test results and analysis.

The term "bridge load capacity" was examined and found to contain a degree of ambiguity, meaning either the limit of elastic behavior or ultimate load capacity. Accordingly, the effects of the variables considered were evaluated in terms of both definitions with emphasis on the limit of elastic behavior. It should be noted that no tests were performed and no sophisticated analytical procedure developed as a part of NCHRP Project 12-28(8). The effect of lateral distribution of load is treated in some detail in this report because (1) some decision as to how the load will be distributed laterally must be made for any bridge being rated, and (2) an overly conservative method for distributing load laterally will result in an unreasonably low estimate of capacity for that bridge. While the investigators fail to identify any major source of hidden load capacity to tap, several potential sources of load capacity enhancement are identified and discussed. These sources include, among others, the effects of unintended composite action, unintended continuity, and skew. Unfortunately, quantifying the effects of the unintended composite action and unintended continuity may be difficult without benefit of some sort of load testing. Whether or not the potential benefits from the results of such testing will justify the time, effort, and expense involved is, of course, a question that must be answered for a particular situation.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

BACKGROUND

Approximately 17 years ago a program of periodic inspections of bridges in the United States was begun. This program has evolved through the years to include within its scope most of the bridges currently in service in this country. An integral part of the bridge inspection program as it exists today is an evaluation guide developed by the Federal Highway Administration (FHWA). Based on an inspection of a bridge, that bridge is rated according to FHWA guidelines and assigned some rating that identifies, within the limits of accuracy of the rating system, the condtion of the bridge.

One very important factor in the evaluation process is the determination of the load-carrying capacity of a bridge. An accurate assessment of this capacity is both critical and difficult—critical because many bridge engineers look at this quantity as the single most important consideration in determining whether a bridge should be left in service or not, and difficult because, frequently, information relating to some of the important variables that affect the capacity of a bridge is not generally available to the people charged with making this assessment.

If the results of a typical inspection and evaluation process lead to the conclusion that a structure is deficient and that replacement of the structure may be appropriate, further study of the condition of the bridge and a more detailed consideration of actual load-carrying capacity are generally justified. Replacement of any bridge is expensive, and if the bridge is on a major traffic artery, the expense is magnified by the inconvenience created in the replacement. Further inspection and analysis—even expensively extensive inspection and analysis—are frequently justified.

A problem inherent in making the "further analysis" which might very well result in keeping a bridge in service is the lack of adequate information needed to define a realistic structural model to calculate load capacity. However, considerable testing of bridge components and some testing of full-scale bridges have been done. These tests have led to numerous published reports which describe bridge behavior in the elastic range and to a few reports which describe this behavior from zero load to failure. The objectives of this research project (NCHRP Project 12-28(8)) were to: (1) assemble, review, and summarize available bridge load test data; (2) identify areas of observed behavior that are not now considered in load capacity estimates which merit further study; and (3) make recommendations regarding the improvement of current methodology for calculating bridge load capacity.

RESEARCH APPROACH

In pursuing the aforenamed goals, the research effort was divided into five tasks. The first two tasks were as follows: (1) to assemble and review relevant test data and any other information available relating to load capacity for a number of different bridge types; and (2) to identify those aspects of behavior which can produce significant variations in load capacity compared to that calculated by current methods. An interim report describing the results of Tasks 1 and 2 was prepared under Task 3. The work under Task 4 involved the assimilation of the information obtained in earlier tasks. Primary emphasis was placed (1) on the identification of those variables not normally considered but which can have a significant effect on load capacity and (2) on the limits of applicability of those variables. This final report incorporates much of the information presented in the interim report as well as the results of the work done under Task 4.

Discussion of Issues Related to Bridge Load Capacity

To attempt to define specific, detailed methodology for the calculation of load capacity for specific bridge types is to go beyond the scope of this research project. Thus, this project has not attempted to make a comprehensive review or rewrite of existing load evaluation techniques. Instead, the project has dealt with the identification of aspects of behavior not currently accounted for, consideration of which will enhance the accuracy of prediction of bridge load capacity.

Early on in the research, the investigators examined the term "load capacity" and found that it does not have a universally accepted, unique meaning. To the authors of this report, the term "bridge load capacity" means simply "the largest load a bridge can support." Another way to phrase this particular definition is to say that the "ultimate load carrying capacity" of a bridge is that load beyond which an increase in bridge deflection results in a decrease in load. Such a concept of capacity is consistent with current practice in the design of both steel and concrete buildings under American Institute of Steel Construction (AISC) or American Concrete Institute (ACI) specifications.

When the proposal for NCHRP Project 12-28(8) was written, the proposers had in mind the definition of "bridge load capacity" just presented. Discussion with bridge engineers with the Tennessee Department of Transportation raised questions about whether such a definition was indeed the most appropriate one or whether more attention should be focused on some point on the load-deflection curve for a bridge that might represent the load at which the bridge begins to behave inelastically. Further conversations between the co-principal investigator on this project and the various bridge engineers and researchers, including some panel members on NCHRP Project 12-28(8), confirmed two facts: (1) the researchers on Project 12-28(8) should indeed give considerable attention to a definition of

"bridge load capacity" that considers the limit of elastic behavior; and (2) apparently, there does not exist a single, universally accepted, unambiguous definition of the term "bridge load capacity."

A typical load-deflection curve for a bridge is shown in Figure 1. Three points of interest labeled on the curve are: (1) the design load; (2) the limit of elastic behavior; and (3) the ultimate capacity. For a well-designed bridge, the design load is well below the limit of elastic behavior and is not the subject of interest in this research effort. However, the other two points are both of interest. The limit of elastic behavior, usually first yield of the tensile steel, could be taken as the limit of useful load-carrying capacity and, as such, could be considered the "load capacity" of interest in this research. But ultimate capacity as a measure of the safety factor inherent in bridge design is also of interest. Thus, this research effort has been concerned with both the limit of elastic behavior and the ultimate capacity, with particular emphasis on the former. However, although this emphasis turned out to be most useful, the problem is made somewhat more difficult because of the difficulty of determining the limit of elastic behavior from test data. A number of bridge load-deflection curves obtained from field test data are shown in Appendix A. While in each case an approximate value for the load causing first yield can be determined, it is clear from the curves presented that a precise value is usually not obtainable.

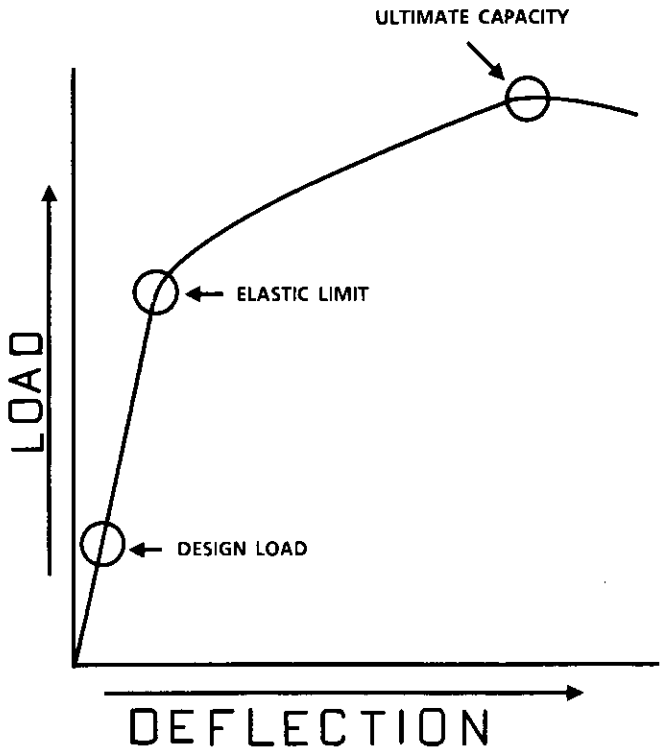


Figure 1. Idealized load-deflection behavior of a bridge.

Review of Literature

One of the major tasks in this research project was to assemble and review pertinent literature relating to bridge load capacity. Special emphasis was given to literature reporting a comparison between test data and analytical approaches. Information about tests on full-size structures was obtained, but only a few bridges were found to have been tested to the inelastic region. Of interest, also, were tests of models, but only results from models of the bridge were examined in detail and not tests on components. Tests on single girders or other portions of the bridge were normally not included in the bibliography. However, publications pertaining to tests on components related to specific topics examined in Task 4 of the project were included.

Details of the test results were obtained from the publications and, in certain cases, the authors of the reports were contacted by phone to further investigate details not clearly described in the publication. The effects of assumptions in the analyses were examined, and independent calculations were performed to aid the researchers' understanding of the problems associated with the comparisons of test results and analysis. The effects of different variables for particular bridge types were also investigated.

The annotated bibliography presented in Appendix B includes research, performed between 1929 and 1987 and representing a broad spectrum of brige types. Table 1 is a summary of the literature surveyed and provides a ready reference source to the annotated bibliography. It is arranged according to the 11 variables considered; for example, if the reader is interested in the participation of parapets and railings for prestressed concrete beam and slab bridges, there are two references related to the ultimate strength tests on full-scale bridges, eight references on service load tests, and one reference on an analytical analysis.

Of all the references listed in Appendix B, the following ones were of particular interest. Extensive bibliographies were included in Refs. *5* (State-of-the-Art Report on Redundant Bridge Systems, 1985); *6* (State-of-the-Art Report on Ultimate Strength of I-Beam Bridges, 1975); *62* (Timber Bridges: State-of-the-Art, 1983); *99* (Test of Half-Scale Highway Bridge Continuous Over Two Spans, PCA Report, 1961); *157* (Structural Behavior of Beam-Slab Highway Bridges—A Summary of Completed Research and Bibliography, Lehigh Report, 1973). Results of full-scale tests to failure are adequately described in the following references:

- Bakht (*8*): Manitou Bridge, Ontario, Canada.
- Bakht and Csagoly (*12*): Perley Bridge, Ontario, Canada.
- Beal (*19, 20*): Jack-Arch Bridge, New York.
- Burdette and Goodpasture (*26*): Four Beam-Slab Bridges, Tennessee (steel, composite; prestressed concrete, composite; reinforced concrete; steel, noncomposite).
- Fullarton and Edmonds (*53*): Mangateweka Stream Bridge, New Zealand.
- Gosbell and Stevens (*57*): Prestressed Beam-Slab Bridges, Australia.
- Jorgenson and Larson (*78*): Slab Bridge, North Dakota.
- Phillips (*111A*): Barkers Bridge, New Zealand.
- Sanders et al. (*119, 120, 121*): Truss Bridge, Iowa.
- Scanlon and Mikhailovsky (*122A*): Reinforced Concrete Bridge, Alberta, Canada.
- Yan (*155*): Karaka Creek Bridge, New Zealand.
- Page (*108C*): Arch Bridges, England.

Large-scale models were tested and reported in Refs. *99* (Test of Half-Scale Highway Bridge Continuous Over Two Spans,

Table 1. References by bridge type and investigative variable.

VARIABLE	BRIDGE TYPE	TEST TYPE	REFERENCE NO.
1 UNINTENDED COMPOSITE ACTION	BEAM AND SLAB -STEEL	ULTIMATE	26F, 138AM, 148DM
		SERVICE	84F, 11P, 143F, 45A, 12F
		OVERLOAD	
	BOX GIRDER -PRESTRESSED CONCRETE	ULTIMATE	
		SERVICE	146F
		OVERLOAD	
	JACK ARCH	ULTIMATE	19F, 20F
		SERVICE	
		OVERLOAD	
	TRUSS	ULTIMATE	
		SERVICE	109F, 142F
		OVERLOAD	
2 PARTICIPATION OF PARAPETS AND RAILINGS	BEAM AND SLAB -PRESTRESSED CONCRETE	ULTIMATE	57F, 26F, 111AF
		SERVICE	48F, 32F, 148F, 157F, 147F, 44F, 61F, 159F, 122A
		OVERLOAD	
	BEAM AND SLAB -REINFORCED CONCRETE	ULTIMATE	25F, 53F, 155F, 78F, 26F
		SERVICE	157F, 122A
		OVERLOAD	
	SLAB	ULTIMATE	
		SERVICE	98BF
		OVERLOAD	
	BEAM AND SLAB -STEEL	ULTIMATE	26F
		SERVICE	92F, 22F, 23F, 85F, 86F, 77M, 157F, 122A
		OVERLOAD	
	BOX GIRDER -PRESTRESSED CONCRETE	ULTIMATE	
		SERVICE	33F, 146F, 59F, 101A, 60F, 94F
		OVERLOAD	
3 DIFFERENCES BETWEEN ACTUAL AND ASSUMED MATERIAL PROPERTIES	BEAM AND SLAB -PRESTRESSED CONCRETE	ULTIMATE	57F, 26F, 111AF
		SERVICE	2M, 47F
		OVERLOAD	87F
	BEAM AND SLAB -REINFORCED CONCRETE	ULTIMATE	25F, 53F, 155F, 78F, 26F
		SERVICE	
		OVERLOAD	
	BEAM AND SLAB -STEEL	ULTIMATE	26F
		SERVICE	97F
		OVERLOAD	
	BOX GIRDER -PRESTRESSED CONCRETE	ULTIMATE	
		SERVICE	146F
		OVERLOAD	102F
4 PARTICIPATION OF BRACING AND SECONDARY MEMBERS	BEAM AND SLAB -PRESTRESSED CONCRETE	ULTIMATE	57F, 26F
		SERVICE	30M, 31F, 32F, 148F, 157F, 147F, 44F, 94F, 64A
		OVERLOAD	
	BEAM AND SLAB -ORTHOTROPIC PLATE DECK	ULTIMATE	
		SERVICE	83F
		OVERLOAD	
	BEAM AND SLAB -REINFORCED CONCRETE	ULTIMATE	26F
		SERVICE	157F, 64A
		OVERLOAD	
	BEAM AND SLAB -STEEL	ULTIMATE	93M, 26F
		SERVICE	22F, 23F, 85F, 86F, 103F, 12F, 157F, 64A, 84F, 138F
		OVERLOAD	
	BOX GIRDER -REINFORCED CONCRETE	ULTIMATE	125M, 126M
		SERVICE	71F
		OVERLOAD	
	BOX GIRDER -PRESTRESSED CONCRETE	ULTIMATE	
		SERVICE	146F
		OVERLOAD	
	TRUSS	ULTIMATE	
		SERVICE	142F, 38A
		OVERLOAD	
5 TWO-WAY SLAB ACTION	BEAM AND SLAB -REINFORCED CONCRETE	ULTIMATE	78F
		SERVICE	
		OVERLOAD	
6 CONFINEMENT		ULTIMATE	17M, 18M
		SERVICE	
		OVERLOAD	88A
7 DIFFERING SUPPORT CHARACTERISTICS AND UNINTENDED CONTINUITY	BEAM AND SLAB -REINFORCED CONCRETE	ULTIMATE	25F, 53F, 155F, 21P, 26F 122AF
		SERVICE	
		OVERLOAD	
	BEAM AND SLAB -ORTHOTROPIC PLATE DECK	ULTIMATE	
		SERVICE	83F
		OVERLOAD	
	BEAM AND SLAB -PRESTRESSED CONCRETE	ULTIMATE	111AF
		SERVICE	48F, 44F
		OVERLOAD	
	BOX GIRDER -STEEL	ULTIMATE	
		SERVICE	35F
		OVERLOAD	
	JACK ARCH	ULTIMATE	19F, 20F
		SERVICE	
		OVERLOAD	

A = ANALYTICAL ANALYSIS ONLY, F = FULL-SCALE IN-SITU (ACTUAL BRIDGE),
P = PROTOTYPE (FULL-SCALE LABORATORIES & MODEL),
M = MODEL (REDUCED SCALE LABORATORY MODEL)

A = ANALYTICAL ANALYSIS ONLY, F = FULL-SCALE IN-SITU (ACTUAL BRIDGE),
P = PROTOTYPE (FULL-SCALE LABORATORIES & MODEL),
M = MODEL (REDUCED SCALE LABORATORY MODEL)

Table 1. Continued

VARIABLE	BRIDGE TYPE	TEST TYPE	REFERENCE NO.
	BEAM AND SLAB -STEEL	ULTIMATE SERVICE OVERLOAD	 11P, 12F, 14AF
8 PARTICIPATION OF FLOOR SYSTEM WITH CHORDS OF TRUSSES	TRUSS	ULTIMATE SERVICE OVERLOAD	119F, 120F, 121F 109F, 142F, 91A
9 LOAD DISTRIBUTION EFFECTS	BEAM AND SLAB - PRESTRESSED CONCRETE	ULTIMATE SERVICE OVERLOAD	57F, 26F, 42AA, 108BA 72F, 29F, 100M, 48F, 30M, 31F, 32F, 148F, 157F, 147F, 44F, 64A, 158A, 159F, 43A, 73A, 72AA, 100AA 90F, 99M
	BEAM AND SLAB - STEEL	ULTIMATE SERVICE OVERLOAD	114M, 104M, 96M, 24M, 26F, 42AA, 108BA 22F, 23F, 85F, 86F, 103F, 138F, 70F, 105A, 11P, 143F, 89F, 50A, 69F, 12F, 4F, 157F, 73A, 64A, 72AA 100AA 151A, 63M
	BEAM AND SLAB -ORTHOTROPIC PLATE DECK	ULTIMATE SERVICE OVERLOAD	 83F, 55F
	BEAM AND SLAB -REINFORCED CONCRETE	ULTIMATE SERVICE OVERLOAD	25F, 53F, 155F, 78F, 21P, 26F, 42AA, 108BA 157F, 73A, 64A, 72AA, 100AA
	BOX GIRDER -REINFORCED CONCRETE	ULTIMATE SERVICE OVERLOAD	127M, 128M, 129M, 130M, 131M, 132M, 133M, 134M, 135M, 136M, 137M, 126M 71F, 55F, 149M
	BOX GIRDER -STEEL	ULTIMATE SERVICE OVERLOAD	 35F, 46F
	BOX GIRDER -PRESTRESSED CONCRETE	ULTIMATE SERVICE OVERLOAD	 33F, 152F, 123F, 146F, 59F, 101A, 60F, 94F, 61F, 47F
	SOIL-STEEL STRUCTURE	ULTIMATE SERVICE OVERLOAD	 9F, 13F
	TRUSS	ULTIMATE SERVICE OVERLOAD	119F, 120F, 121F 109F, 142F, 49F
	JACK ARCH	ULTIMATE SERVICE OVERLOAD	19F, 20F
	RIGID FRAME	ULTIMATE SERVICE OVERLOAD	 82F
	WAFFLE SLAB	ULTIMATE SERVICE OVERLOAD	79M

VARIABLE	BRIDGE TYPE	TEST TYPE	REFERENCE NO.
10 EFFECTS OF DETERIORATION	BEAM AND SLAB -REINFORCED CONCRETE	ULTIMATE SERVICE OVERLOAD	127M, 128M, 129M, 21P 108AF
	BEAM AND SLAB -PRESTRESSED CONCRETE	ULTIMATE SERVICE OVERLOAD	 43A 87F
	BEAM AND SLAB -STEEL	ULTIMATE SERVICE OVERLOAD	58M 143F, 89F
	BOX GIRDER -REINFORCED CONCRETE	ULTIMATE SERVICE OVERLOAD	137M
	RIGID FRAME	ULTIMATE SERVICE OVERLOAD	 139F
	TRUSS	ULTIMATE SERVICE OVERLOAD	 109F
11 EFFECTS OF SKEW	BEAM AND SLAB -REINFORCED CONCRETE	ULTIMATE SERVICE OVERLOAD	26F 157F, 61AA
	BEAM AND SLAB -PRESTRESSED CONCRETE	ULTIMATE SERVICE OVERLOAD	 123F, 146F, 157F, 147F, 44F, 61AA 87F
	BOX GIRDER -REINFORCED CONCRETE	ULTIMATE SERVICE OVERLOAD	125M, 133M, 134M, 135M, 136M 149M
	BOX GIRDER -STEEL	ULTIMATE SERVICE OVERLOAD	 35F
	BEAM AND SLAB -STEEL	ULTIMATE SERVICE OVERLOAD	58M 105A, 77M, 157F, 61AA
	SLAB	ULTIMATE SERVICE OVERLOAD	 76AA, 98BF
	ORTHOTROPIC SLAB	ULTIMATE SERVICE OVERLOAD	80AA, 148EA

PCA Report), and Refs. (*125*) through (*136*) (University of California, Berkeley Tests on Box Girders). Several tests were helpful for obtaining information relative to load distribution, namely, *72A* (Imbsen and Associates, NCHRP Report, Project 12-26); *99* (PCA Report); and *118* (Sanders and Elleby, NCHRP Report 83).

It should be noted that no tests were performed in the course of the research and no sophisticated analytical procedure was developed as a part of this project. Thus, the published literature cited in the annotated bibliography played an especially important role in the research documented in this final report.

CHAPTER TWO

FINDINGS

The problem of identifying, quantifying, and documenting the effects of a number of variables on the load-carrying capacity of a bridge has been approached from the viewpoint of an engineer charged with the rating of a bridge and faced with the situation where a bridge's calculated load-carrying capacity is lower than that needed to keep the bridge in normal service. In such a case the engineer is faced with a dilemma that might be resolved if he or she were able to calculate a more realistic, and larger, load capacity. Perhaps, a more detailed investigation is warranted in a particular case, and the engineer in such a case needs to know what to look for to identify some aspect of behavior that might lead to a larger capacity than originally calculated. The information included in this report is presented in a way intended to be helpful to an engineer in the situation just described. For each bridge type, the variables deemed to be of particular importance are identified, the limits of applicability are discussed, and the potential for this variable's enhancing bridge load capacity is addressed.

There are some variables inherent in the determination of bridge load capacity which relate to essentially all bridge types. A brief discussion of the potential importance of some of those variables is presented in the following paragraphs.

GENERAL VARIABLES

Material Properties

In the design of a bridge, certain properties must be assigned to the materials used in the structure. As most bridges consist of steel and/or concrete, key properties are the tensile strength of the steel and the compressive strength of the concrete. Because of the necessity that actual strengths be at least as high as design strengths to a high level of confidence, strength values used in design cannot be taken as the average values for a particular concrete mix or grade of steel but must be taken as somewhat less than those values. Thus, actual material strengths are, typically, significantly higher than design strengths. This fact is illustrated by the data presented in Table 2.

When a bridge must be posted or removed from service, the engineer may perform more refined analyses, obtain samples of the bridge for better evaluations of strength, and conduct tests on the bridge to help keep the bridge in service. For instance, fatigue limits in the design code are based on statistical data from laboratory tests on steel girders. Most evaluations of bridge strength are based on the minimum specified yield or ultimate strength of the steel. An increase in capacity may be realized if the yield strength is taken to be the mean value less two standard deviations for that type of steel. This would ensure that 95 percent of the yield strengths would be greter than the value used.

In order to predict accurately the behavior of a specific structure, the analyst must know as precisely as possible the actual material properties associated with that structure. In order to predict analytically the response of a particular structure for a specific test condition, the mean value of the actual material properties would be expected to provide the most reliable results. In order to analyze the structure for a particular loading condition and to predict with some confidence that the structure would be safe to withstand the applied loads, the mean value less some multiple of the standard deviation for the actual properties should be used. It is not the intent of this research to establish factored resistance criteria; however, it is important in comparison of measured and computed response made as a part of this research that actual values of material properties be used to predict structural response.

From the viewpoint of an engineer trying to find a rational way to increase the calculated load capacity of a particular bridge, consideration of actual material properties instead of those used for design purposes may hold some potential. The determination of these actual properties may or may not be worth the effort and expense to obtain them. If it turns out after an investigation that the steel in either a reinforced concrete bridge or steel girder bridge is significantly stronger than the strength used in design, an appreciable increase in calculated load capacity will result. On the other hand, an actual concrete strength higher than that assumed in design will typically have only a small effect on the flexural strength of either deck or girders. An increase in concrete strength will have an effect on shear capacity—which would be helpful in the unlikely event that shear controlled the overall bridge capacity—and on the capacity of members such as piers loaded in axial compression and bending. For a truss bridge a significant increase in actual steel strength over assumed could prove to be very helpful. In

a timber bridge an increase in wood strength over that assumed could be very helpful also, but obtaining appropriate values to use for wood under different loadings might require considerable effort. In any specific case, the question of whether to expend the necessary effort and money to obtain actual material properties will probably not have an obvious answer, but there are occasions where the question should at least be raised.

Effects of Deterioration

The degree of deterioration of a bridge is obviously not a variable that stands to enhance bridge capacity, but rather it is one that stands to decrease it. The assessment of deterioration of a bridge is an important part of the current bridge inspection and evaluation process. While this subject barely fits under the topic of this research project, a brief discussion of the effects of deterioration is included herein as Appendix E. The information presented in this appendix notes that, while a reasonable and conservative estimate of the effects of deterioration on load capacity is important, some test data show that these effects frequently are of less importance than cursory observation might indicate.

Computer Analysis

Computer programs have been developed in the past few years that enable the engineer to examine the bridge as an entire structure, rather than just investigating the components alone. Loads may be carried by the bridge system due to redundancy not originally accounted for. Higher fatigue loads may also be allowed for multi-load-path bridges. However, the engineer must ask himself whether the failure mode is a ductile type or a brittle type, because most computer codes used for bridge analysis do not warn him of sudden failures. Another factor which affects the ability of the analyst to accurately predict the capacity of a bridge is the proper discretization of the truck wheel loads. The researchers performed analyses several years ago relating finite element analyses to bridge tests and found that much better predictions of behavior were obtained when all 18 wheel loads were used instead of 6 or 10 load points for a tractor-trailer truck. The curbs also needed to be accurately modeled with the computer evaluation. The use of the New Jersey type barrier may also add additional section modulus; however, the engineer must make sure that the barrier can resist longitudinal loads, i.e., there are not too many expansion joints.

Strain Hardening

The primary focus of the research effort reported herein has been to identify important, often neglected aspects of behavior which lead to enhanced "load capacity," the latter being most usefully defined as the upper limit of elastic behavior or "first yield" of the tensile steel. In the calculation of load capacity so defined, strain hardening of steel does not take place; thus, no consideration of it is made. If, however, for any reason an attempt is made to calculate the "ultimate capacity" of a bridge, consideration of strain hardening becomes very important. Most reinforced concrete bridges are under-reinforced; that is, the amount of tensile steel is kept relatively low. In such a bridge the tensile steel can be expected to be stretched well into the

Table 2. Differences between actual and assumed material properties.

CONCRETE PROPERTIES

REFERENCE NO.	SPECIFIED f'c (KSI)	MEASURED f'c (KSI)
26 (BRIDGE 1)	3.0	6.87
26 (BRIDGE 2)	3.0	5.5
26 (BRIDGE 3)	3.0	6.5
26 (BRIDGE 4)	3.0	5.6
47	6.0	7.02
52	5.4	6.5
56	2.5	7.25
57	5.0	7.0
78	3.0	6.86
88	3.5	5.75
103	5.75	6.9
111A	2.5	6.8
142	3.0	4.97
156	2.5	7.8

STEEL PROPERTIES

REFERENCE NO.	SPECIFIED fy (KSI)	MEASURED fy (KSI)
26 (BRIDGE 1)	36	40
26 (BRIDGE 4)	36	40
56	30	45
78	40	53
103	40	50
111A	30	40
156	30	45

PRESTRESSING STRAND PROPERTIES

REFERENCE NO.	SPECIFIED (KSI)	MEASURED (KSI)
2	fu = 246	fu = 277
52	fy = 160	fy = 210
103	fu = 270	fu = 284

strain hardening range before failure. In a steel bridge, strains well into the range of strain hardening generally occur before the ultimate load of the bridge is reached. The stress in the steel for both concrete and steel bridges is, therefore, significantly larger at ultimate stress than the yield stress, a fact that contributes measurably to the ultimate load-carrying capacity. Thus, to make an accurate determination of ultimate capacity requires a consideration of strain hardening, a consideration that requires a knowledge of the stress-strain relationship for the steel. Unfortunately, the latter may not be readily available without obtainaing samples from the existing structure.

While consideration of strain hardening results in a larger and more nearly correct prediction of ultimate capacity, it is of little help to the engineer looking for a way to calculate a larger "bridge load capacity" in order to keep a bridge in service. The reason, as noted earlier, is that the bridge load capacity the engineer is generally interested in occurs at steel strains less than that at which strain hardening would begin. Thus, the discussion presented here is useful primarily to the person trying to match calculated ultimate loads to ultimate loads obtained in a test to failure of a bridge.

BEAM AND SLAB BRIDGES

This bridge type includes reinforced concrete T-beam bridges, bridges with reinforced or prestressed concrete beams either composite or noncomposite, steel beams and slab either composite or noncomposite, and box girder bridges. This broad category includes a majority of bridges in service today and an even larger majority of new bridges. In the sections that follow, a number of variables are considered, each one with the potential for increasing the calculated load capacity of a bridge beyond that normally considered.

Load Distribution

The term, load distribution, is used to refer to the lateral distribution of load to longitudinal supporting elements. How applied loads distribute themselves laterally to the beams in a beam and slab bridge has a significant effect on the magnitude of those loads required to produce first yield of tension steel. Similarly, how a bridge rating engineer assumes that the applied loads will be distributed has a signficant effect on the load capacity that he or she calculates.

Suppose, for example, that an engineer assumes a conservative distribution of load such that an interior girder in a beam-slab bridge is considered to support an unrealistically large portion of the total load. The load required to produce first yield in an interior girder will then be taken as the load capacity of the bridge. Because of the unrealistic assumption of load distribution, this calculated capacity is not an accurate representation of the true load capacity of the bridge and is unrealistically low. If a load test is performed on the bridge, the measured load capacity will surely be larger than that calculated. If the analyst is unaware of the conservatism inherent in the load distribution used in the analysis, a question is then raised as to why measured capacity was larger than calculated capacity. Unintended continuity perhaps? In-plane forces that led to enhanced capacity? These influences, indeed, may have been contributors. But, given the initial supposition in this example, an inaccurate assumption concerning the distribution of loads to the supporting girders is certainly one contributor to the disparity between measured and computed capacities. How large a contributor this inaccurate assumption is depends, of course, on the degree of inaccuracy.

From the preceding example the argument is made that, while lateral distribution of load is not really an "aspect of behavior," a reasonably accurate method for assigning loads to supporting members is necessary if accurate predictions of bridge load capacity are to be made. The AASHTO *Standard Specifications for Highway Bridges* (13th edition, 1983) present criteria for lateral distribution of load that are generally considered to be conservative. These criteria, conservative or not, are intended for design purposes; a bridge rating engineer is concerned not with design but with analysis. Thus, some adjustment to the approach presented in the AASHTO *Standard Specifications* must be made to achieve results that are not grossly conservative, and the development of additional methodology for lateral distribution of load to enhance the accuracy of load capacity calculations could prove to be useful.

Some work on this subject, which grew out of the research conducted under Project 12-28(8), is presented in Appendix C of this report. It is based on work by Guyon (*62A*) and by Massonnet (*98A*) and culminates in a series of influence coefficients which may be used to determine lateral load distribution factors. NCHRP Project 12-26 (*72A*) is being performed concurrent with this project. Project 12-26 is an intensive study of the distribution of wheel loads on highway bridges and is expected to provide extensive data on the subject. Although load distribution is not the primary focus of this research, it does prove to be an area where significant enhancement in calculated load capacity can be gained by properly distributing the wheel loads on the structure. The case studies, presented in Appendix C, illustrate the methodology and document the effect of different methods of assigning lateral loads.

The results presented in Appendix C show a modest increase in load capacity predicted and, in turn, in accuracy of prediction using the distribution coefficients presented. It should be noted, however, that the comparison made is with a simplified method which, for the cases compared, was reasonably good. If the AASHTO coefficients were used directly with no modification, the predicted capacities based on AASHTO would have been significantly lower, and a correspondingly larger increase in predicted load capacity using the influence coefficients would have resulted.

Unintended Composite Action

This aspect of behavior is one generally considered to hold considerable potential for enhancing bridge load capacity for bridges with steel girders and concrete decks. Bridge 4 in the Tennessee bridge tests (*26*) was a steel girder, concrete deck bridge designed to act noncompositely. In fact, analysis of the data showed clearly that this bridge acted compositely up to the point that yield in the steel girders would have occurred in the noncomposite bridge. These rather widely publicized results have contributed to the belief apparently held by many engineers that composite action will exist in a beam and slab bridge whether it was provided for in the design or not. Because this

belief does appear to be widely held and because the subject of composite action deserves special attention, a reasonably thorough treatment of the subject is included in Appendix D of this report. The work presented in Appendix D leads to the following statements which may be useful to a bridge engineer charged with calculating the capacity of a bridge.

1. Composite action in a bridge designed to act noncompositely cannot be counted on to increase significantly the load capacity of a bridge if that capacity is defined as the load-producing first yield of tensile steel. In Tennessee Bridge 4 (*26*) the load capacity was simply the sum of the capacities of the four steel girders. The path from zero load to yield, on the other hand, was significantly affected by the presence of composite action. The bridge was effectively much stiffer than calculated on the basis of noncomposite behavior; thus, at any load level below yield, the deflection was much less than calculated. This behavior relates also to stresses: it follows that the stress in the steel girders at any load below yield in Tennessee Bridge 4 was less than that calculated on the basis of noncomposite behavior. Therefore, even though unintended composite action does not appreciably enhance load capacity, in the process of altering the behavior of a bridge in the elastic range, it does reduce the stress in the girders at any load level. This reduction in stress for a given load may very well prove to be of significant benefit to a bridge engineer concerned with bridge load capacity.

2. The discussion just presented was based on the existence of unintended composite action like that found in Tennessee Bridge 4. In fact, the work presented in Appendix D leads to the conclusion that composite behavior in a bridge designed with no provision for composite action may or may not occur. In some cases the practical and conservative approach is to disregard any potential unintended composite behavior. For the cases where such an assumption leads to calculated stress levels for certain required loadings that are larger than permitted, further investigation to verify the presence of composite action may be justified. Such an investigation would logically begin with an inspection of the bridge by an experienced bridge engineer, an inspection that would include visual observation of the beam-slab interface as truck traffic goes over the bridge. Details of construction should be observed; for example, encasement of the top flanges of the steel girders would increase the probability of composite action. This investigation may very well prove to be inconclusive. In such a case the next step might be to load the bridge statically with a heavily loaded truck of known dimensions and weight and to measure deflections of the bridge at selected points. Comparison of the measured deflections with deflections calculated on the basis of both noncomposite and composite action should shed considerable light on the question of whether the bridge is behaving compositely or noncompositely. If composite action is found to exist, this behavior can be considered in the calculation of stresses at various load levels below that used in the test. The possibility of sudden slippage at loads greater than the test load makes the assumption of composite action at higher load levels questionable.

Unintended Continuity

Unintended continuity is the tendency of a bridge to act as though it were continuous at the ends when it was designed to be simply supported. By this definition unintended continuity is of importance only in simple span bridges, either single or multiple span, or at the ends of continuous bridges.

In simple span steel girder bridges, any continuity at a support comes from some unintended resistance to rotation such as rusted pins in pinned joints or rocker arms cocked out of position. There are no test data available to shed much light on the amount of additional load capacity that might be obtained from unintended continuity in simple span steel bridges. Work by Barton and McKeel (*14A*) clearly showed that some allowance for end moment had to be made in order for predicted load-deflection behavior to match measured load-deflection behavior in the elastic range. They concluded, however, that it was impossible to predict, without test data, how much continuity effect actually existed. In some cases where the effort is justified, a significant increase in calculated load capacity may be obtained by some load tests to determine the amount of continuity present.

In reinforced concrete simple span bridges, the effect of unintended continuity resulting from the in-plane action produced either by adjacent beams or by an abutment may be significant. In both the Tennessee tests (*26*) and New Zealand tests (*25*), there was a significant difference between calculated and measured capacities of the simple span reinforced concrete T-beam bridges. Later calculations on Tennessee Bridge 3 showed that applying approximately 35 percent of full fixity at the ends resulted in a much closer matching of calculated and measured load-deflection curves. Interestingly, a similar percentage of full fixity would have given a close correlation between measured and computed capacities for the New Zealand bridges also.

The presence of axial restraint at the ends of reinforced concrete bridges actually enhances capacity two ways: (1) the end moment obviously adds to the capacity, and (2) the axial compression causes a sort of tied arch behavior that enhances capacity. In both the New Zealand and Tennessee tests, this enhancement was significant.

The problem of deciding whether to count on this phenomenon without the benefit of full-scale test data is, unfortunately, not easy to solve. The Tennessee bridge was tested on a very hot afternoon in July when the bridge would have been expanded about as much as it had ever been. If the test had been performed in January, the effect of continuity might have been considerably less. Of course, the effect of friction at the beam bearing points will always be present, but the larger effect of actual butting of the ends of the beams is less dependable. A thorough examination of the ends of a bridge in question should be made before any effect of unintended continuity is counted on. Sometimes joints at bridge ends are grouted, in which case some continuity can be counted on with a high degree of confidence. Typically, even after an examination is made, no more than 15 to 20 percent of full fixity should be assumed unless some load testing is done to justify a higher percentage.

Confinement. As the term *confinement* was used in the NCHRP Project Statement, it referred to the restraint provided by surrounding elements, typically concrete, to lateral displacement of the bottom fibers of a beam or slab subjected to positive bending moment. The "unintended continuity" just discussed for Tennessee Bridge 3 is an example of "confinement." Another example of confinement is the restraint offered to a bridge deck by adjacent beams when the deck is loaded between beams with a wheel load. The *Ontario Highway Bridge Code* accounts for

this kind of confinement by specifying a low percentage of reinforcement for flexure in deck slabs and considering that punching shear is the controlling mode of failure. New York State research (*17, 18*) agrees with this concept. However, analytical work by Kostem (*88*) disagrees with this approach—but whether or not Kostem's finite element model was capable of considering the effect of inplane forces is not clear.

The significance of the preceding discussion of confinement to an engineer charged with rating a bridge depends on which element of the bridge controls the load capacity. If flexure of the deck is the controlling consideration, attention to the New York tests and the Ontario Highway Bridge Code recommendations would be expected to lead to a substantial increase in calculated capacity by increasing the load calculated to reach the elastic limit in bending. Emphasis would then shift to evaluating capacity based on punching shear in the deck or on the overall flexural and shear capacities of the bridge.

Effects of Skew

Reports relating to the analysis of beam and slab bridges were reviewed to determine the effect of skew on the moment capacity of a bridge. The definition of the angle of skew used in this report is the angle between the abutment and a line perpendicular to the edge of the bridge; that is, a right angle crossing is a zero degree skew. The University of Illinois (*106*) found that an increase in the skew angle caused a reduction of the maximum moment in the beams for an applied load. It was also found that the capacity of the slab with a 60-deg skew angle was less than that for 0 deg or 30 deg. Additionally, it was noted that the deflections of a skewed bridge were smaller than in a right bridge (*123*). The effect of skew is relatively small on a slab and girder bridge, the most significant change occurring with skews greater than 45 deg (*61A*).

Test results from the University of Illinois, along with other collected data, are presented in Table 3. The table shows the percent moment reduction due to the change in skew angle. These data show the moment reduction for a given skew angle compared to a right bridge of the same type. It was found that the percent increase in moment for the slab in a beam and slab bridge was between 8 and 27 percent for a 30 deg skew, and between 23 and 34 percent for a 60 deg skew (*106*).

The data in Table 3 show that the moment reduction is not in agreement for the various tests, indicating there are factors other than the skew angle that need to be considered before a better estimate of capacity considering effects of skew can be found. One of the factors is the length-to-width ratio, which has an effect on the results (*43*). Each case has various factors that affect the outcome, and additional experimental research or a finite element analysis would be needed to obtain a more precise answer for the reduction of moment for each skew angle.

Table 3. Percent reduction of moment of a beam in a beam and slab for a given skew angle comparable to a right bridge.

	30° Skew	45° Skew	60° Skew
Non-Composite } Illinois Tests	9%	-	28%
Composite [106] } Illinois Tests	-5% *	-	16%
Finite difference solution by Chen, Siess, and Newmark [148A]	17.8%	22.8%	30.7%
Slab 44 (Discrete Element) [148E]	1.0%	4.0%	14.1%

* Percent Increase in Moment

Parapets and Railings

The presence of parapets and bridge railings acting integrally with the deck has the effect of stiffening the outside girders on a beam and slab bridge, thus attracting more load to these girders. Under a typical bridge loading condition, the interior girders generally take more load than the outside girders; thus, the attraction of more load to the outside griders plus the general stiffening of the bridge cross section has the effect of adding to a bridge's load-carrying capacity at first yield. The question is whether a particular parapet or railing can be counted on to act integrally with the deck all the way to yield of the tensile steel. Many rails of the 50's and 60's vintage, particularly, are of a design that has very little stiffening effect on a bridge cross section. On the other hand, a rail with the stable configuration of a New Jersey barrier can add a significant amount to the stiffness of a cross section unless too many expansion joints in the rail disrupt its continuity. The 1937 model bridge rail on Tennessee Bridge 4 had the effect of adding an appreciable amount to the bridge's load-carrying capacity at first yield. But because of the inability of the slender vertical posts to transfer the necessary horizontal shear, the railing had little effect on ultimate strength.

Before a bridge engineer can count on a particular parapet or railing to enhance the load capacity of a bridge in question, an assessment must be made of (1) how securely the rail is tied in with the curbs or deck and (2) whether or not the rail's configuration is adequate to transfer the necessary horizontal shear to cause it to act as a composite part of the bridge deck and girder system all the way to yield. This is an assessment that, typically, can and should be made for any bridge being analyzed. If the rail can be counted on to act compositely to yield, this can add a significant amount to the calculated capacity. The percentage added depends on a number of factors including the rail itself, the width of the bridge deck, and the size and stiffness of the supporting girders.

SLAB BRIDGES

When the span of a bridge is relatively short, less than 30 ft or so, a slab bridge may be used. The riding surface of the bridge is the top face of the slab, and there are no girders used to transmit the loads to the supports. In some cases voids are introduced in the slab. As the spans get longer, slab bridges are not an efficient or economical way to support the design loads. Slab bridges are normally reinforced by reinforcing bars, but prestressing strands and I-beams have been used. In many cases the width of the slab may equal or exceed the span of the bridge. In cases where the bridge width is equal to or greater than the span, then plate behavior of the bridge should be taken into

account. Approximations that include one-way slab action may not reflect the behavior of the slab. Torsional moments in the slab must be considered particularly when the bridge is skewed. The corners of the slab tend to move upwards due to a downward load in the center portion of the slab.

Reports related to testing of skewed slab bridges were studied to determine the effect of the moment capacity of the bridge. The definition of the angle of skew used in this report is the angle between the abutment and a line perpendicular to the edge of the bridge; that is, a right bridge is a zero degree skew. It was found that the moment due to a uniform load will decrease as the skew angle increases (*80A*). An applied concentrated load has less effect than a uniform load on the decrease in moment (*80A*). Most of the results show that the effect on moment with a skew angle less than 45 deg is negligible, but the moment reduction for skews greater than 45 deg could affect the design of a bridge or the evaluation of bridge load capacity (*58*). This reduction of moment in a skewed bridge is largely dependent on the length-to-width ratio. Thus, each case, depending on the skew angle and the length to width ratio, is different.

The University of Illinois has done research on the analysis of skew slabs with the use of finite difference equations. Their analysis showed a decrease in moment with an increase in the skew angle. A simply supported, uniformly loaded slab with free edges was analyzed for skew angles of 0 deg, 30 deg, 45 deg, and 60 deg. The reductions with a length-to-width factor of 2.0 for a 30 deg, 45 deg, and 60 deg skew, were 27, 41, and 66 percent, respectively (*76A*). These moment reductions are significant and should be considered in the determination of bridge load capacity. No actual tests were studied in the references used; therefore, only theoretical data were considered in this analysis of skewed slabs.

It is known that the moment decreases as the skew angle increases, but the reduction becomes more important for skew angles greater than 45 deg. However, in some cases a 30 deg skew could provide enough reduction to merit consideration. Because of several factors involved, the exact amount of moment reduction is uncertain with each skew angle; thus, a more refined analysis is required to determine a better prediction of capacity. A relatively simple finite element analysis is one way to determine a more precise reduction in moment due to the effect of skew.

TRUSS BRIDGES

Trusses have been used for many years for longer spans of highway bridges. Usually a truss is analyzed as an ideal truss, and the effects of floor systems and bracing are not considered in the evaluation. However, when a bottom chord of the truss has deteriorated or has been damaged by impact from a truck or ship, the floor beam system may sustain the load even though the chord has completely failed in tension or from impact. A three-dimenstional analysis considering the primary truss members, the floor system, and the bracing will, in all probability, indicate an increase in the capacity of the truss. A few tests have been performed on trusses, notably the tests to failure on two old trusses in Iowa (*49, 119, 120, 121*), and service load tests on Pony trusses in Ontario, Canada.

Both of the trusses tested in Iowa were single-lane bridges. Tests were performed to investigate the performance under service loads. The comparison between the test results and analyses was not very close, a fact attributed to the rusting of the pins at the joints. Ultimate load tests were performed on the timber deck of the Hubby bridge (*121*). Eyebars were removed and both static and fatigue tests were performed on them (*120*). Two pony trusses were subjected to service loads on Ontario (*109, 142*). The deck was a concrete slab cast over stringers and floor beams. Calculated floor beam moments were much higher than the measured values. Corrections were made for load sharing using Bakht and Jaeger's method to obtain reasonable results. The tests on the Perley bridge (*12*) in Ontario indicated that the joints were also frozen by rust, and the analytical results were not close to the test results.

A better evaluation of the capacity of a truss may be obtained if the complete structure is included in the analysis. A simply supported truss is normally a redundant structure due to the bracing and floor system. Therefore, a more realistic analysis may be made by performing a three-dimensional elastic analysis. Critical members of the truss may be identified and their mode of failure examined. The failure of a highly stressed member may result in a local deformation of the roadway rather than complete collapse of the bridge. However, when assessing the capacity of a bridge, the engineer responsible for the rating of the truss must be aware of the consequences of the failure of a truss member.

CHAPTER THREE

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The annotated bibliography presented in Appendix B represents a significant portion of the results of the research described in this report. This bibliography is a compilation of a large number of references related to bridge load capacity, and each reference is described in enough detail to enable the user of the bibliography to decide whether or not a particular reference merits being located and studied more thoroughly.

The major results of this research, as determined from the

Table 4. Summary of factors influencing bridge strength estimates.

Variable \ Bridge Type	Beam and Slab	Concrete Slab	Truss	Box Girder
Unintended Composite Action	P, I/T	N/A	S[1], I/T	P, I/T
Participation of Parapets and Railings	P, A	P, A	N/A	P, A
Differences Between Actual & Assumed Material Properties	S, I/T	S, I/T	S, I/T	S, I/T
Participation of Bracing and Secondary Members	S	N/A	S	S
Two-Way Slab Action	N/A	S	N/A	N/A
Confinement	S[2]	N/A	S[2]	S[2]
Differing Support Characteristics and Unintended Continuity	S, I/T	S, I/T	S, I/T	S, I/T
Participation of Floor System with Chords of Trusses	N/A	N/A	S, I/T	N/A
Analysis/Load Distribution Effects	P, A	P, A	P, A	P, A
Effects of Skew	S, A	P[3]	N/A	S, A

KEY
- P - Primary Factor
- S - Secondary Factor
- A - Include in Conventional Analysis
- I/T - Inspection and or Testing Needed to Verify
- N/A - Not Applicable

1 Composite Action Between Floor Beams and Concrete Deck
2 Influences Local Deck Strength Only
3 Short Span Bridges Only (S for Longer Span Bridges)

reference works identified and studied, were discussed in Chapter Two of this report. Those results are presented in a way intended to be useful to a bridge engineer charged with the responsibility of rating a bridge and thus determining whether a particular bridge should be allowed to remain in service. A summary of the effects of several variables on load capacity is presented in Table 4. The subject of lateral load distribution of longitudinal supporting elements is treated in some detail in Chapter Two, even though the subject does not represent either an "aspect of behavior" or a "variable" which affects the capacity of a bridge. Lateral load distribution is included as an important part of this study because (1) some decision as to how the load will be distributed laterally must be made for any bridge being rated, and (2) an overly conservative method for distributing load laterally will result in a calculation of capacity for that bridge which is unreasonably low. Thus, a reasonably accurate assignment of lateral loads to supporting members is an important element in the process of calculating bridge load capacity.

Nowhere in the course of reviewing the research reports relating to the calculation of bridge load capacity or in their own previous research did the investigators find any major source of hidden load capacity waiting for some imaginative bridge rating engineer to tap. There are some potential sources of capacity beyond those normally considered in typical bridge rating calculations; those sources identified and studied as a part of this research are listed and discussed in Chapter Two. Unfortunately, as noted therein, to quantify the effect of some of the most important variables such as unintended composite action or unintended continuity in many cases will require that some load testing be done on a particular bridge. Whether or not the potential benefits from the results of such testing will justify the time, effort, and expense involved is, of course, a question that must be answered for a particular situation.

SUGGESTED RESEARCH

The question of whether or not composite action can be counted on in a bridge not designed for composite action is one which continues to arise but which is almost impossible to answer definitely and confidently without benefit of some sort of load testing. The potential benefits from being able to count on unintended composite action up to near yield are significant, a fact that suggests that research directed toward the identification and quantification of this phenomenon may be justified. Such research could be directed toward the development of a relatively simple test procedure to determine if composite action exists in a particular bridge and to evaluate approximately the degree of reliability of that composite action up to the load level of interest. The test procedure would need to be developed and verified using full-scale bridges. The development of a reliable and simple test procedure as discussed would have far reaching economic benefits for those situations where the load on a bridge is limited by the stress level calculated in the girders. In such cases the presence of composite action where none was intended would reduce the calculated stresses significantly.

APPENDIX A

BRIDGE LOAD-DEFLECTION CURVES

Presented in this appendix are a number of experimental load-deflection curves for bridges that were tested beyond the elastic limit into the inelastic range of behavior. The curves were taken directly from the references cited. Some of the curves were obtained from monotonic loading and others from cyclic loading; in some cases calculated curves are presented for comparison. While most of the curves consist of a portion almost linear followed by a curved, inelastic portion, the shape of the curves and the relationship between first yield and ultimate vary widely. The curves also illustrate the difficulty in identifying from test data the load at which essentially elastic behavior ends.

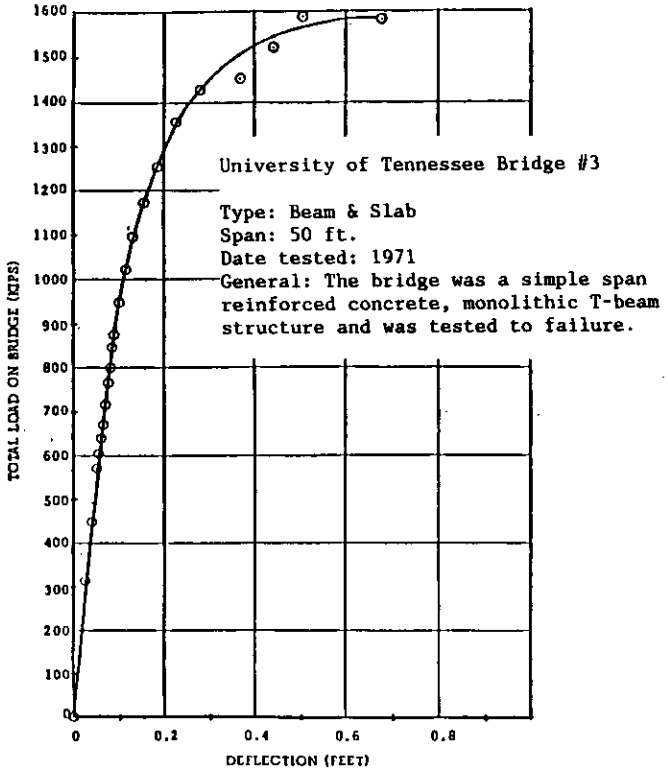


Figure A-1. Load-deflection curve reprinted from Ref. 26.

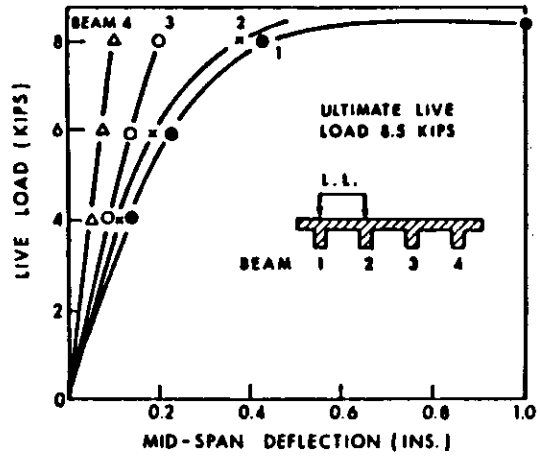


FIG 43 SPAN DEFLECTIONS, LOAD CYCLES 1—7

Ontario Beam & Slab Bridge Models

Type: Beam & Slab
Span: 6 ft.
Date tested: 1970
General: 1/10 scale model of a 60 ft. span 2 lane bridges and tested to failure.

Figure A-2. Load-deflection curve reprinted from Ref. 93.

Mangateweka Bridge

Type: Beam & Slab
Span: 31.5 ft.
Date tested: 1981
General: The bridge was a reinforced concrete T-beam structure with four girders and was tested to failure.

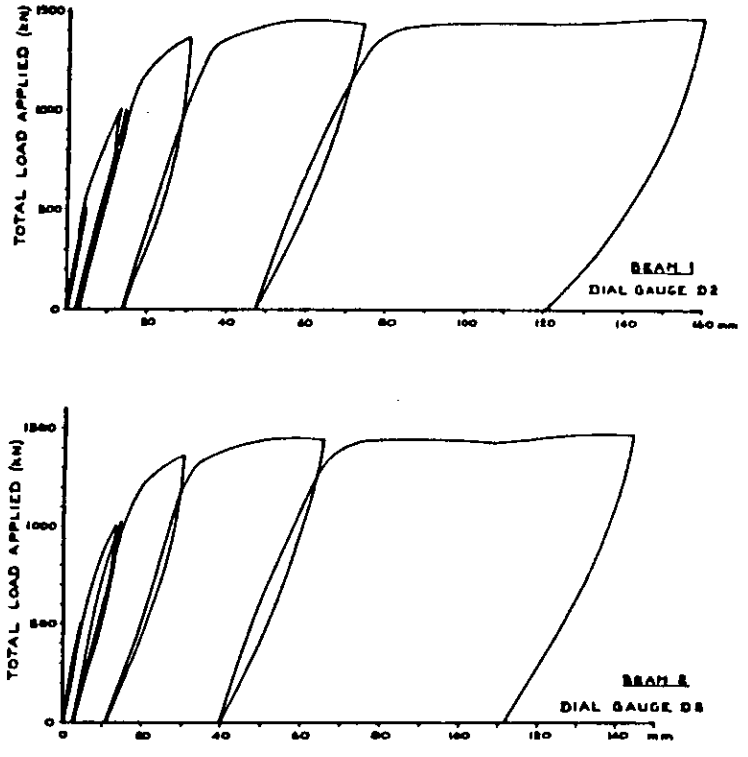


Figure 17, Relation Between Live Load and Deflection, Specimen No. 6

Figure A-3. Load-deflection curve reprinted from Ref. 53.

Karaka Creek Bridge

Type: Beam & Slab
Span: 30 ft.
Date tested: 1982
General: The bridge was a reinforced concrete T-beam structure with four girders and was tested to failure.

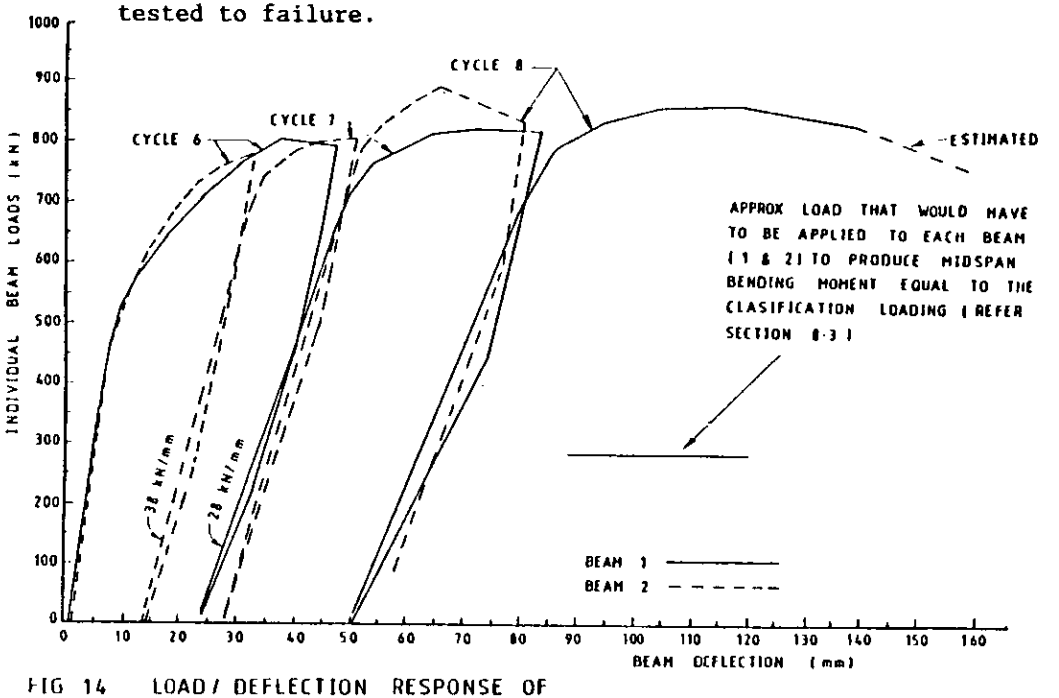


FIG 14 LOAD / DEFLECTION RESPONSE OF BRIDGE BEAMS UNDER HIGH JACK LOADS

Figure A-4. Load-deflection curve reprinted from Ref. 155.

Barkers Bridge

Type: Beam & Slab
Span: 42 ft.
Date tested: 1985
General: The bridge was a reinforced concrete T-beam structure with four girders and was tested to failure.

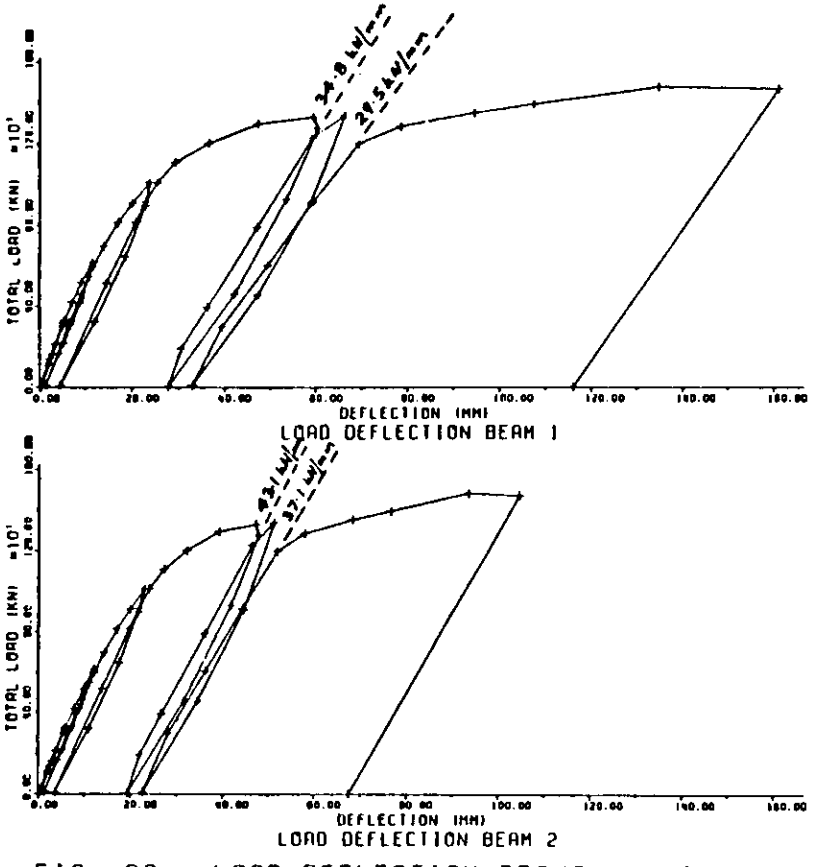


FIG. 22 LOAD DEFLECTION BEAMS 1 & 2

Figure A-5. Load-deflection curve reprinted from Ref. 111a.

Sandy Creek Bridge

Type: Beam & Slab
Span: 58' 10"
Date tested: 1968
General: The seven girder prestressed concrete bridge was tested to failure.

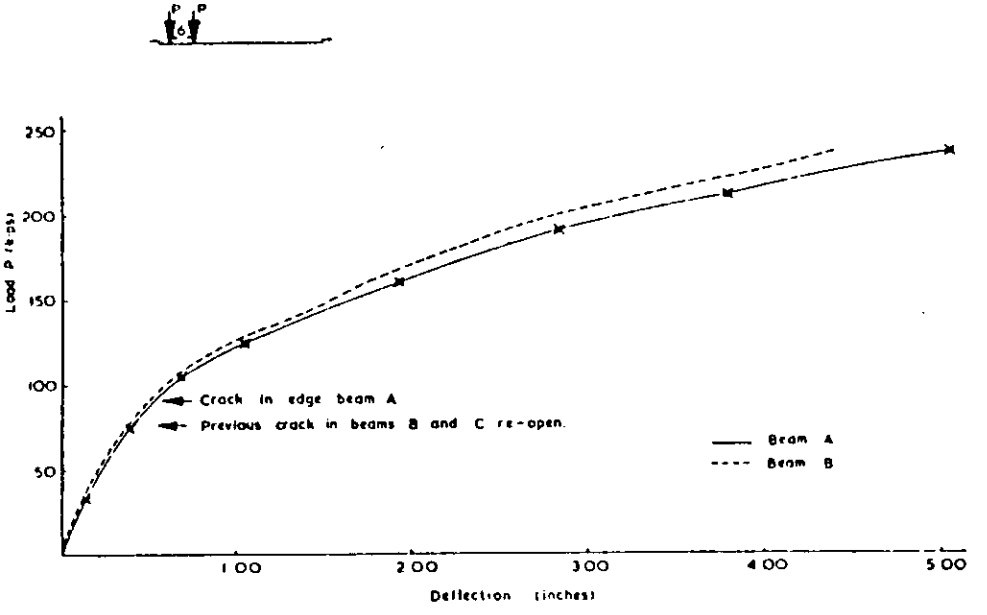


Fig. 12 — Load deflections curve for ultimate test (west lane)

Figure A-6. Load-deflection curve reprinted from Ref. 57.

University of Tennessee Bridge #2

Type: Beam & Slab
Span: 66 ft.
Date tested: 1971
General: The bridge was a simple span composite structure with AASHTO type III precast, prestressed concrete beams, and was tested to failure.

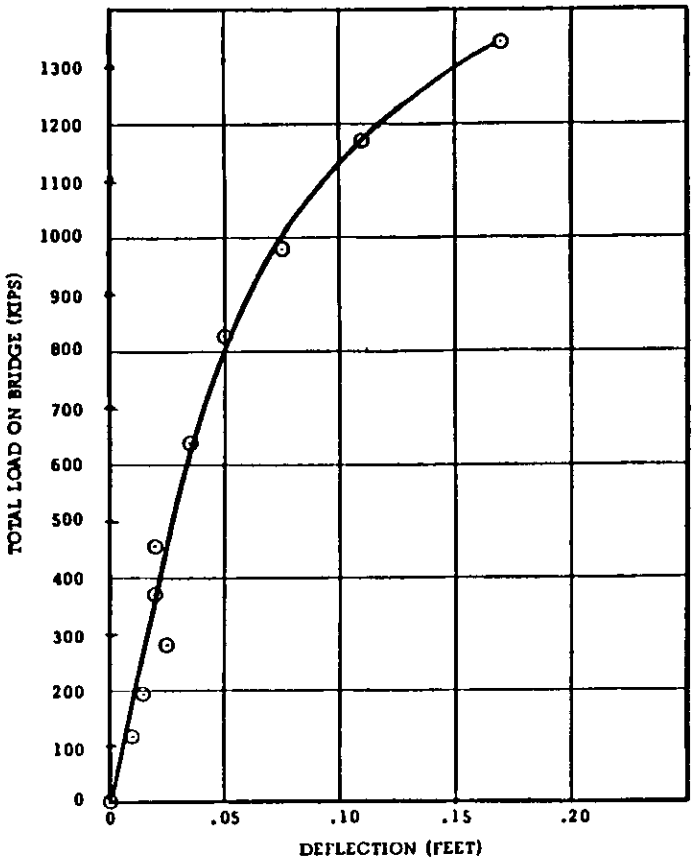


FIGURE 38. LOAD-DEFLECTION CURVE - CENTERLINE OF SPAN AT CENTER OF ROADWAY - BRIDGE 2 (Test No. 2400).

Figure A-7. Load-deflection curve reprinted from Ref. 26.

Pennsylvania DOT Experimental Segmental Bridge

Type: Beam & Slab
Span: 121 ft.
Date tested: 1982
General: The two girder post tensioned segmental bridge was tested to failure.

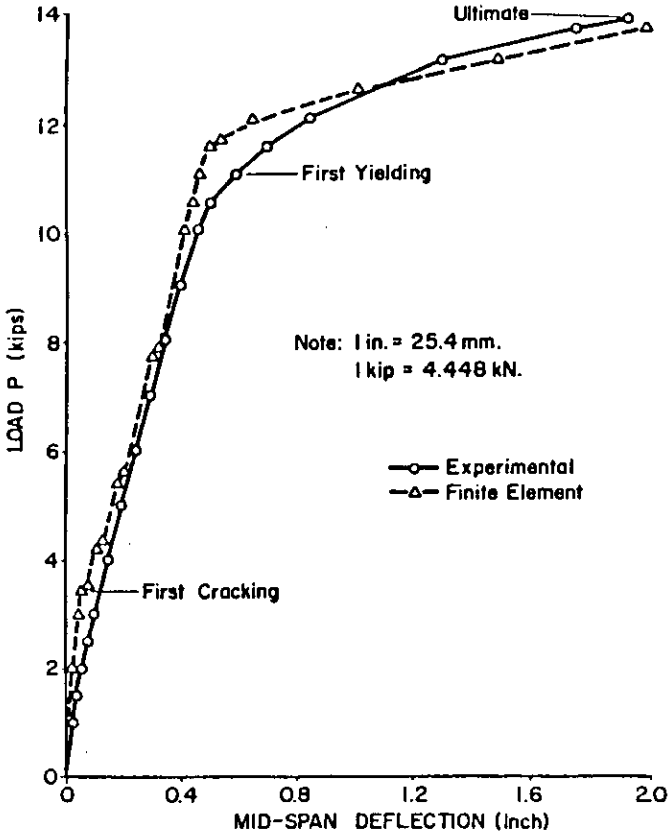


Figure 33. Load-Deflection Curve for the Simple Beam

Figure A-8. Load-deflection curve reprinted from Ref. 102.

Reinforced Concrete Box Girder Bridge Model

Type: Beam & Slab
Span: 36 ft.
Date tested: 1971
General: The model was a 1:2.82 scale replica of a typical California Highway System prototype.

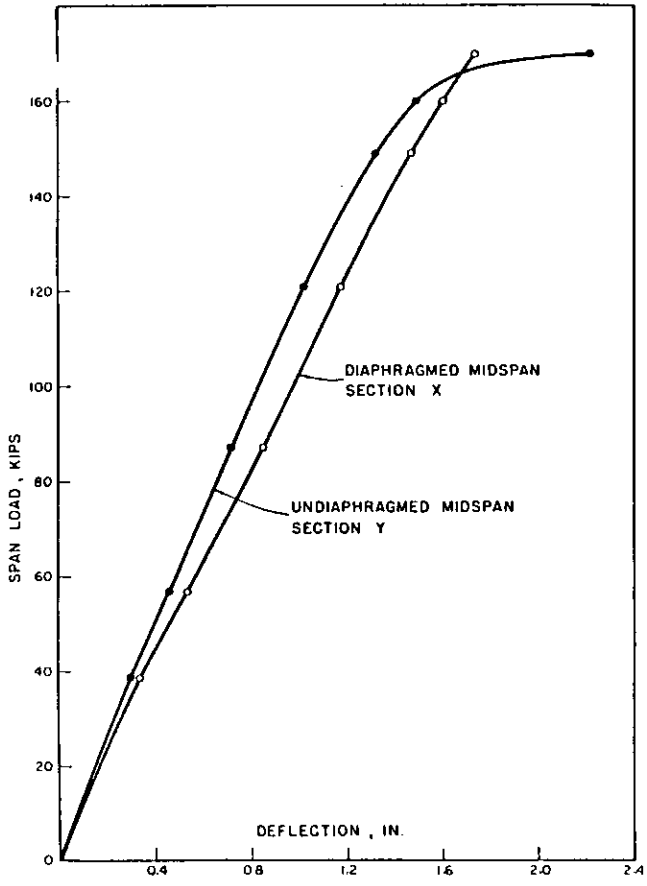


FIG. 82 LOAD-DEFLECTION GRAPHS FOR GIRDER 1 AT MIDSPAN

Figure A-9. Load-deflection curve reprinted from Ref. 131.

Reinforced Concrete Skew Box Girder Bridge Model

Type: Beam & Slab
Span: 36 ft.
Date tested: 1971
General: The model was a 1:2.82 scale replica of a typical California Highway System prototype.

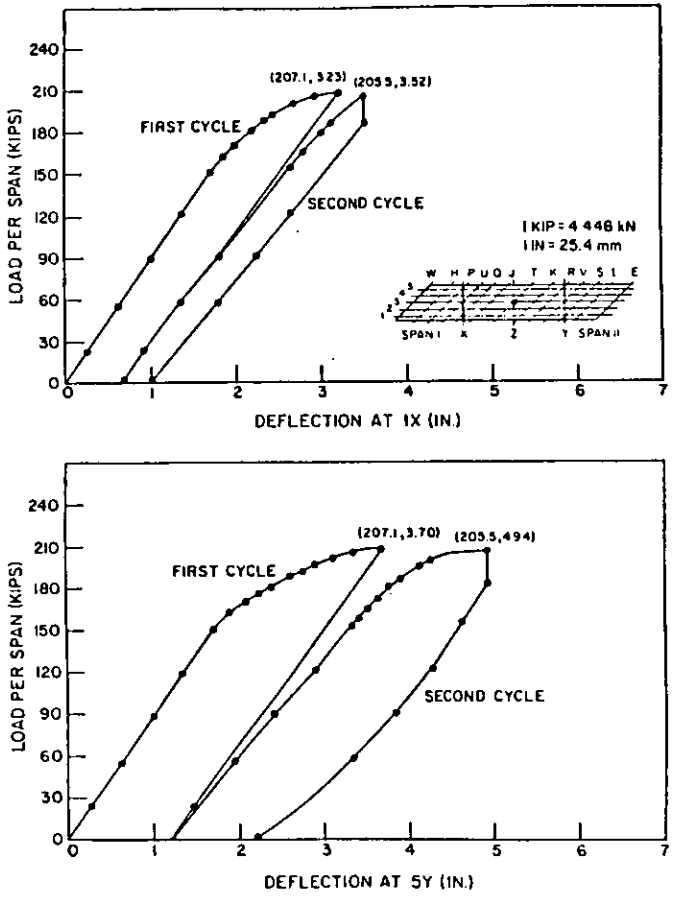


FIG. 3.12 LOAD DEFLECTION DIAGRAM AT 1X AND 5Y DURING FIRST AND SECOND CYCLES OF ULTIMATE LOADING - BOTH SPANS LOADED

Figure A-10. Load-deflection curve reprinted from Ref. 134.

Reinforced Concrete Curved Box Girder Bridge
Model

Type: Beam & Slab
Span: 36 ft.
Date tested: 1971
General: The model was a 1:2.82 scale replica of a typical California Highway System prototype.

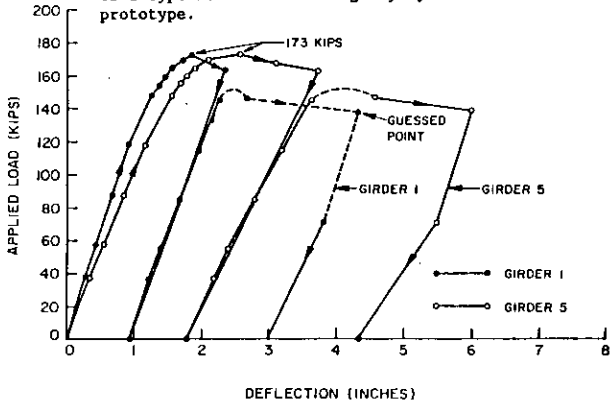


FIG. B.11 LOAD-DEFLECTION DIAGRAM AT SECTION Y FOR GIRDERS 1 AND 5 DURING FIRST AND SECOND LOADING CYCLES -BOTH SPANS LOADED

Figure A-11. Load-deflection curve reprinted from Ref. 128.

University of Tennessee Bridge #1
Type: Beam & Slab
Span: 70-90-90-70 ft.
Date tested: 1971
General: The bridge was a 4-span continuous structure with four 36 in. steel rolled beams and was tested to failure.

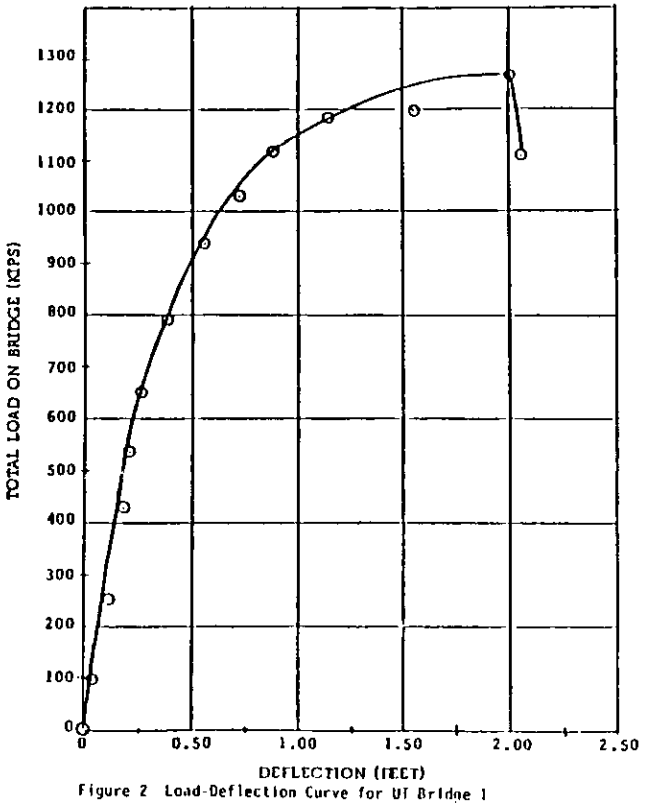
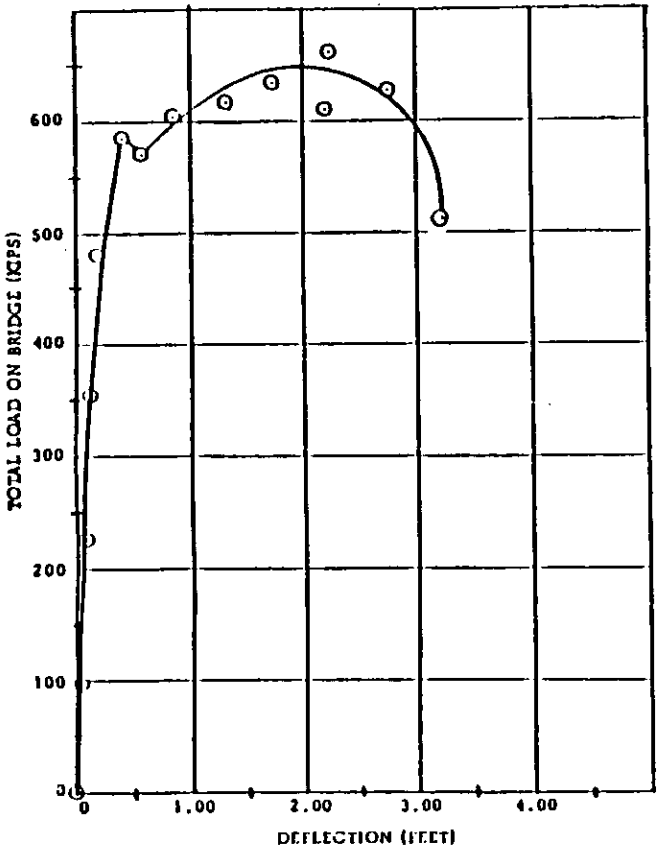


Figure 2 Load-Deflection Curve for UT Bridge 1

Figure A-12. Load-deflection curve reprinted from Ref. 26.

University of Tennessee Bridge #4

Type: Beam & Slab
Span: 45-60-45 ft.
Date tested: 1971
General: The bridge was a 3-span continuous, non-composite structure with four 27 in. steel rolled beams and was tested to failure.



Load-Deflection Curve: Centerline of Span at Center of Roadway

Figure A-13. Load-deflection curve reprinted from Ref. 26.

Continuous Composite Bridge Models 2-Span

Type: Beam & Slab
Span: 9-9 ft.
Date tested: 1977
General: The model consisted of three S 6X12.5 steel beams reinforced with 5 X 3/8 in. cover plates top and bottom.

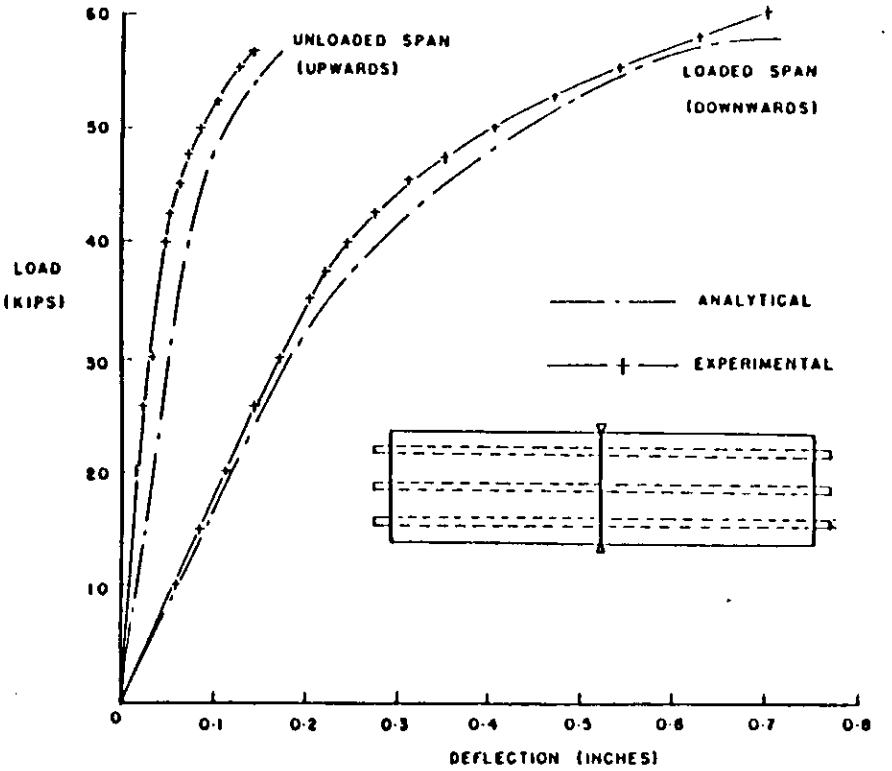


FIG. 6.—Comparison of Deflections: Two-Span Case (1 in. = 25.4 mm; 1 kip = 4.45 kN)

Figure A-14. Load-deflection curve reprinted from Ref. 24.

Continuous Composite Bridge Models 3-Span

Type: Beam & Slab
Span: 6-6-6 ft.
Date tested: 1977
General: The model consisted of three S 6X12.5 steel beams reinforced with 5 X 3/8 in. cover plates top and bottom.

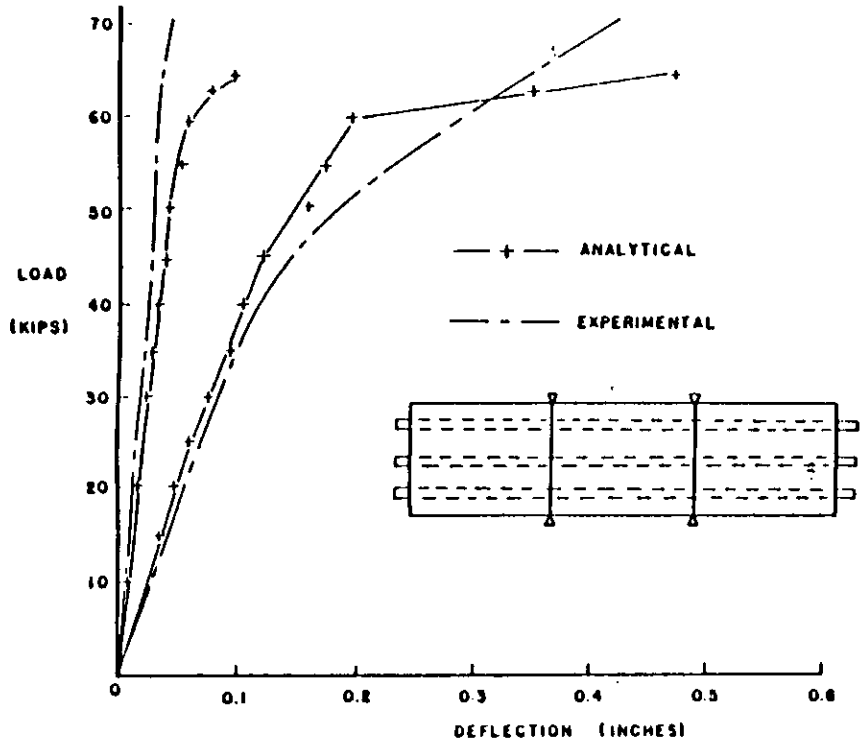


FIG. 8.—Comparison of Deflections: Three-Span Case (1 in. = 25.4 mm; 1 kip = 4.45 kN)

Figure A-15. Load-deflection curve reprinted from Ref. 24.

19 ft. Precast Bridge Slab

Type: Slab
Span: 19 ft.
Date tested: 1954
General: The 19 ft. precast slab was tested to failure.

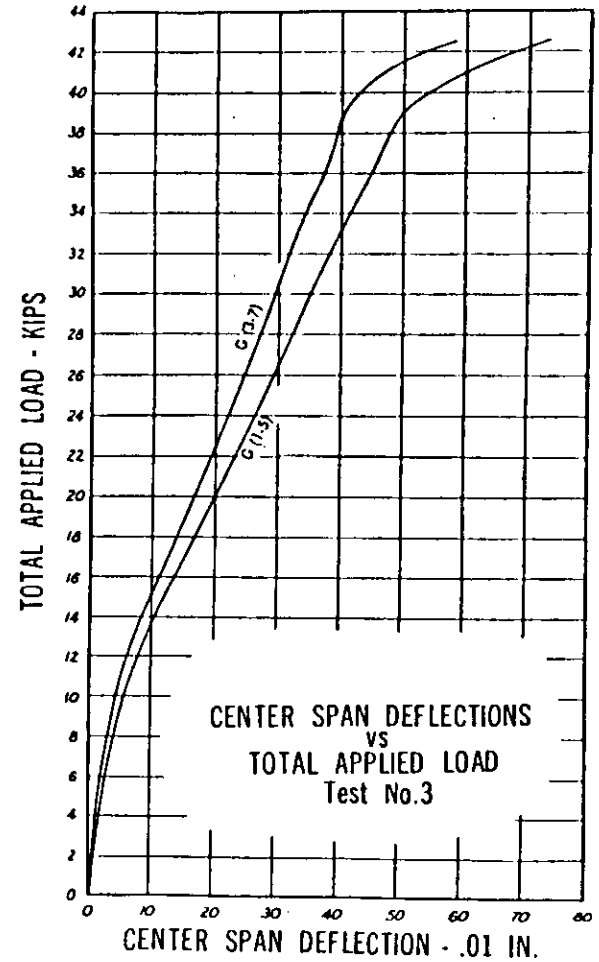


Figure 16. Center span deflections of girders on a single 19' precast bridge slab loaded as shown in Figure 13.

Figure A-16. Load-deflection curve reprinted from Ref. 68.

North Dakota Casselton Bridge

Type: Rigid Frame
Span: 20-25-20 ft.
Date tested: 1974
General: The 3-span 32 ft. wide and 12 in. thick slab bridge was tested to failure.

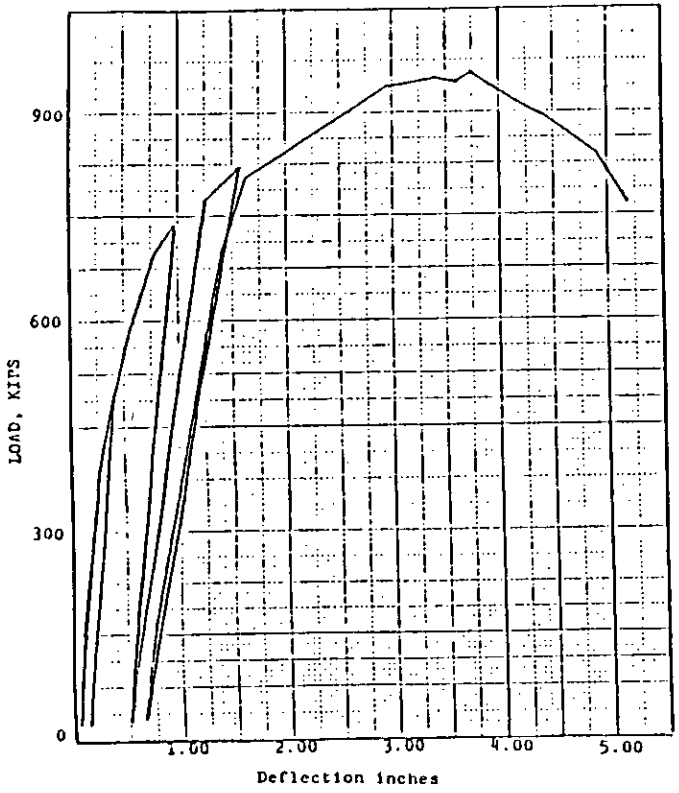


FIGURE 14

LINE LOAD VERSUS DEFLECTION, LOCATION 7

Figure A-17. Load-deflection curve reprinted from Ref. 78.

Hubby Bridge

Type: Truss
Span: 165 ft.
Date tested: 1975
General: The bridge consisted of four modified Parker type high-truss simple spans.

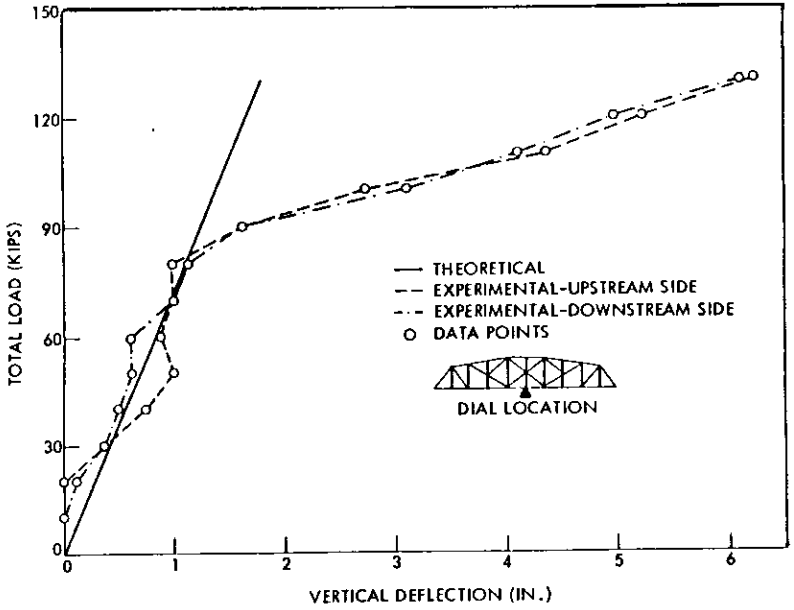
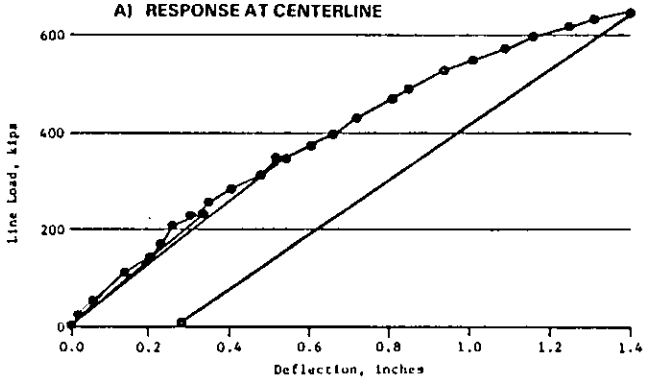


Fig. 57. Total load-vertical deflection at L_5 for truss test.

Figure A-18. Load-deflection curve reprinted from Ref. 121.

Figure 8. Failure test beam deflections.



Indian Lake Bridge

Type: Jack Arch Bridge
Span: 45 ft.
Date tested: 1984
General: Structure had eight 28 in. deep I-beams and was tested to failure.

Figure A-19. Load-deflection curve reprinted from Ref. 20.

APPENDIX B

ANNOTATED BIBLIOGRAPHY

1. AKTAS,Z., VANHORN,D.A., **"BIBLIOGRAPHY ON LOAD DISTRIBUTION IN BEAM-SLAB HIGHWAY BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 349.1, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, SEPTEMBER 1968.

This report presents an investigation on the available literature on field tests, analytical methods, and model studies related to load distribution in beam-slab highway bridges utilizing prestressed concrete I-beams as the main beams. A total of 118 references was included.

2. ANDERSON,T.C., HOUDESHELL,D.M., GAMBLE,W.L., **"CONSTRUCTION AND LONG-TERM BEHAVIOR OF 1/8TH SCALE PRESTRESSED CONCRETE BRIDGE COMPONENTS"**, STRUCTURAL RESEARCH SERIES NO. 384 AND ILLINOIS COOPERATIVE HIGHWAY RESEARCH PROGRAM SERIES NO. 131, UNIVERSITY OF ILLINOIS, URBANA, ILLINOIS, 1972.

This paper describes the construction and observed long-term deformations of two single-span and two three-span continuous composite prestressed concrete models of highway bridge girders. The test girders, 6 in. deep by 9 ft. long, were 1/8 scale models of girders from a highway bridge located in Douglas County, Illinois.

The two three-span structures, representing interior lines of beams from the prototype, were each made with three simply supported girders which were made continuous for live load effects by means of reinforcement in the cast-in-place deck and by concrete in the pier diaphragm.

The effects of continuity in reducing the long-term deformations occurring after the deck concrete was cast were strikingly shown, and it was found that a simple elastic analysis could satisfactorily predict the relative magnitudes and directions of deformations occurring after the deck concrete had hardened.

Creep and shrinkage data for the concretes used in the structures are reported. It was found that the small size of the specimens led to large creep and shrinkage strain values, as were expected. It was also found that the strain prediction methods based on volume-surface ratio effects could not be indiscriminately extended to very thin specimens and members.

3. ANEJA,I.K., ROLL,F., **"MODEL ANALYSIS OF CURVED BOX-BEAM HIGHWAY BRIDGE"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.97, NO.ST12., DECEMBER 1971, PP. 2861-2878.

This paper presents the fabrication, preparation, and instrumentation of a plastic model (Plexiglass 11-UVA) of a horizontally curved box-beam highway bridge. Experimental data for three lane loading conditions were obtained. A finite element computer program based on the displacement method of analysis was used to analyze the model. A comparison between the experimental and theoretical stress distribution across the midspan showed a good agreement between the shapes but not the magnitudes of the stress plots.

4. ANTONI,C.M., CORBISIERO,J.A., **"INSTRUMENTATION AND TESTING OF CONCRETE BRIDGES REINFORCED WITH HIGH-STRENGTH STEEL"**, RESEARCH REPORT 68-3, BUREAU OF PHYSICAL RESEARCH, NEW YORK STATE DOT, ALBANY, NEW YORK, SEPTEMBER 1968.

This paper presents a study to investigate the possibility of improving bridge construction through use of high-strength reinforcing steels. Two cast-in-place concrete bridges, reinforced with high-yield-strength steel were designed, constructed, and instrumented for the test. The test program was designed to provide data that would aid in evaluating bridge performance, and to indicate the improvement in bridge construction, exemplified by two experimental bridges. The two structures tested for this report and reinforced with high-yield-strength reinforcement are performing satisfactorily and in the manner predicted by analysis and model testing.

5. ASCE-AASHTO COMMITTEE, **"STATE-OF-THE-ART REPORT ON REDUNDANT BRIDGE SYSTEMS"**, JOURNAL OF STRUCTURAL ENGINEERING, ASCE, VOL.111, NO.12, DECEMBER 1985, PP. 2517-2531.

This report examines methods to determine the redundant paths in flexural systems, and presents the experience of approximately 100 actual bridge structures. A surprising amount of redundancy was observed in most of these structures. The linear elastic analysis and non-linear analysis of structures are discussed.

This paper also includes some comments for the analyst which were based on various research programs and observations, which were very informative and useful. The committee also made a survey of steel highway and railway bridges reported suffering distress in main load-carrying members. Results of the survey showed that few steel bridges collapse if redundancy is present. The reported collapses involved trusses with essentially no redundancy.

6. ASCE-AASHTO TASK COMMITTEE, **"STATE-OF-THE-ART REPORT ON ULTIMATE STRENGTH OF I-BEAM BRIDGES"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.101, NO.ST5, MAY 1975, PP. 1085-1096.

This is an excellent article detailing latest analysis techniques for beam-slab bridges. Methods of static analysis discussed include the following:

1. ORTHOTROPIC PLATE THEORY - The bridge system is considered to be an elastic continuum and is treated as an equivalent plate.
2. GRID SYSTEM - System is idealized as an equivalent grillage of interconnected longitudinal beams and transverse beams, cross-members, or diaphragms.
3. GIRDER-PLATE REDUNDANT TECHNIQUES - The interacting forces between the slab and longitudinal girders are treated as redundants in the systems.

Experimental studies involving ultimate load testing are referenced. Design information as related to load factor design is discussed. Recommendations for future research are detailed.

7. ASCE-AASHTO TASK COMMITTEE, **"STEEL BOX-GIRDER BRIDGES - ULTIMATE STRENGTH CONSIDERATIONS"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.100, NO.ST12, DECEMBER 1974, PP. 2433-2448.

As a result of recent (1974) bridge failures the subcommittee was formed to evaluate information on failure modes and ultimate strength of steel and composite steel and concrete box girders. The four major failures which occurred since 1969 were as follows:

1. FOURTH DANUBE BRIDGE - VIENNA, AUSTRIA (NOV, 1969).
2. MILFORD HAVEN ROAD BRIDGE - WALES, UNITED KINGDOM (JUNE, 1970).
3. WEST GATE BRIDGE - MELBOURNE, AUSTRALIA (OCT, 1970).
4. RHINE RIVER BRIDGE - KOBLENZ, GERMANY (NOV, 1971).

The primary mode of failure for each of the bridges was instability of the webs. This article has an excellent bibliography on state of the art research on box-girder design and construction.

8. BAKHT,B., **"LOAD CARRYING CAPACITY OF THE MANITOU BRIDGE"**, 80-SRR-1, RESEARCH AND DEVELOPMENT DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, MAY 1980.

The Manitou Bridge located in metropolitan Toronto is owned by the Parks Department of that municipality. The original flooring system (probably wood) was replaced in 1912 with steel cross beams (stringers) and a 4.5" concrete slab. In 1960 the original steel arches and stringers were encased in concrete and additional 2" to 3" topping was added to the deck. The deck has cantilever overhangs beyond the outer arches and several of the supports have developed cracks which caused concern as to their ability to sustain the cantilever loads. These overhangs sometimes are loaded with large numbers of pedestrians. These concerns led to an investigation of the bridges' load carrying capacity.

The initial investigation, by consulting engineers determined that by using conventional analysis methods the deck and cross beams were substandard. Based on the results of their analysis the consultants restricted the bridge loads to 7.5 tons and recommended replacement of the deck and stringers. The owner then contracted with the Ontario Ministry of Transportation and Communications to proof load the bridge. The following tests were performed:

1. Punching shear tests on the deck slab.
2. Testing for pedestrian loads on the cantilever overhangs.
3. Testing for overall vehicle capacity.

The results of the tests were as follows:

1. The encased cross beams and the deck slab are capable of sustaining axle weights of any legally permitted vehicle in Ontario. (Punching Shear Tests)
2. The cast iron brackets are only ornamental and do not support the cantilever portion of the deck slab, which itself can safely support a uniformly distributed load of at least 270 psf. This is 2.6 times the usual pedestrian design loads.
3. The bridge could safely sustain a slow moving vehicle of 75 tons.

CONCLUSION: With minor repairs the bridge is more than adequate for its intended use.

9. BAKHT,B., **"LIVE LOAD TESTING OF SOIL-STEEL STRUCTURES"**, SRR-80-4, POLICY PLANNING AND RESEARCH DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, AUGUST 1980.

The report describes the live load tests on three soil-steel structures (bridges and culverts composed of shells of corrugated steel embedded in an envelope of engineered soil). Some methods of determining live load responses were reviewed.

These include:
Watkins Method
AISI (American Iron and Steel Institute) method
CSPA (California Corrugated steel Pipe Assoc.) method
AASHTO method
Kaiser Aluminum method
OHBDC (Ontario Highway Bridge Design Code) method
Strip Method

A new method for determining live load responses is presented. It is discussed that the new method is as simple as the older methods and yet is able to predict the maximum live load thrust values within a good degree of accuracy.

The three structures discussed are:
White Ash Creek Structure
Deux Rivieres Structure
Adelaide Creek Structure

10. BAKHT,B., **"USE OF SIMPLIFIED METHOD OF ANALYSIS SPECIFIED IN THE OHBDC CODE"**, 79-SRR-8, RESEARCH AND DEVELOPMENT DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, FEBRUARY 1979.

The report describes the Ontario Highway Bridge Design Code (OHBDC) simplified methods for calculation of longitudinal moments, longitudinal shears and transverse moments in bridges of basic form having maximum of 4 lanes.

The basic form bridge is explained in detailed in section 5.4.1 of OHBDC; in summary it is a single span simply supported bridge of rectangular plan form having its longitudinal rigidity distributed fairly uniformly across the width of the bridge.

Report includes some worked examples of different bridge types. These include:
(a) Non-composite beam and slab bridge.
(b) Composite beam and slab bridge.
(c) Continuous slab bridge.
(d) Continuous beam and slab bridge.

Also presented in the report are governing load case charts for live longitudinal moment and shears.

Report contains analysis charts for longitudinal moment and shears, and transverse moments for different size bridges.(eg. 2 lane, 3 lane etc.) The limitations on this method are also discussed.

11. BAKHT,B., CSAGOLY,P.F., **"DIAGNOSTIC TESTING OF A BRIDGE"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.106, NO.ST7, JULY 1980, PP. 1515-1529.

This paper reports on an extensive diagnostic load test that was undertaken to detect the sources of distress in a bridge, and to establish its actual load distribution pattern. The bridge tested was the Perley Bridge. Results have shown that the past failure of the girder-column connection was due to considerable longitudinal stresses in girder webs and connecting angles of the connections. There was partial continuity of girders over supports and even in the absence of mechanical shear connectors, there existed some composite action between the slab and the floor beams.

The authors have demonstrated the use of diagnostic testing to :

1. Locate the sources of distress that might exist in a bridge due to inadvertent component interaction; and

2. Determine the positive effects of component interaction on load distribution.

12. BAKHT,B., CSAGOLY,P.F., **"TESTING OF PERLEY BRIDGE"**, RR 207, RESEARCH AND DEVELOPMENT DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, JANUARY 1977.

This paper describes the load test which was conducted on Perley Bridge, which was a 2284 ft. long bridge of assorted spans in steel. The main objectives of the test were to establish the load-carrying capacity of trestle spans and the bowstring-truss span as governed by their various components. The various components of the trestle span which were investigated were the girders, floor beams and columns.

This report included the test data and a comparison with the analytical results. The details of the instrumentation layout and data acquisition systems were also presented. Suggestions for repairs were made based on the conclusions drawn from this test.

13. BAKHT,B., ZDISLAW,K., **"TESTING OF A SOIL-STEEL STRUCTURE WITH A RELIEVING SLAB"**, SRR-84-4, RESEARCH AND DEVELOPMENT BRANCH, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, 1984.

The report records data from a live load test on a soil-steel structure with a relieving slab. The structure had an elliptical conduit with a span of 30 ft. and a rise of 15 ft.

Response of the structure was monitored through strain gauges on the metallic shell and recorded data consist of live load thrusts and moments computed from measured strains.

Report also contained detailed information about the instrumentation and results are plotted on the diagrams of the structure.

14. BAKHT,B., CSAGOLY,P.F., **"BRIDGE TESTING"**, SRR-79-10, POLICY PLANNING AND RESEARCH DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, AUGUST 1979.

This report contains abstracts of nearly all the bridge tests carried out by the Ontario Ministry of Transportation and Communications until the end of 1977. Over a hundred bridge tests have been carried out which varied from extensive monitoring of all critical components in a bridge under test vehicles to the measuring of only the bridge accelerations under normal traffic. The report also contains brief description of the equipment that was employed during testing operation.

The report concludes that the vast experience of the Ministry in bridge testing has shown that the tests indicated that most bridges possessed strengths far in excess of those predicted by conventional theory. Bridge testing is shown to be useful not only in determining the load carrying capacity of individual bridges but also in checking the validity of rational methods of evaluation in predicting the safe load carrying capacity of similar existing bridges.

14A. BARTON,F.W., McKEEL,W.T.,Jr., **"DEVELOPMENT OF AN IMPROVED CAPABILITY FOR PREDICTING THE RESPONSE OF HIGHWAY BRIDGES"**, FINAL REPORT, VIRGINIA HIGHWAY AND TRANSPORTATION RESEARCH COUNCIL VHTRC 86-R45, JUNE 1986.

This study compared experimental and analytical stress and deflection response of a simply supported highway bridge as measured from a field test and as predicted from a finite-element analysis. The field

test was conducted on one-span of a six-span highway bridge in Virginia using a loaded dump truck as the applied loading. Deflection and strain measurements were recorded at the quarter point and midspan of two adjacent spans with the test vehicle in various positions. A finite-element model of the bridge was then developed in which the bridge deck was represented using the quadrilateral shell elements and the girders were represented by beam elements. Two different versions of the finite-element model were utilized, one assuming simply supported ends, and one in which continuity was included. Nodes were located such that stresses and deflections in the finite-element model could be predicted at locations corresponding to those where experimental data was recorded.

It was found that the measured response and predicted response from the finite-element model with simply supported boundaries did not compare favorably. Differences on the order of 50% or more were typical. Experimental data from the field test had, however, indicated a degree of restraint at the supports corresponding to approximately 10% fixity. When this degree of restraint was included in the finite element model of the bridge, comparison between measured and predicted response improve markedly. The difference between measured and predicted deflections were generally less than 5%. Comparison between measured and predicted stresses were slightly larger although the agreement was still satisfactory.

Results of this study indicate that the overall response of a relatively simple bridge structure can be satisfactorily predicted from rationally developed finite element models. In the formulation of these models, however, considerable attention should be devoted to a realistic representation of the longitudinal and transverse stiffness and particularly to the support conditions of the structure.

15. BASE,G.D., ROWE,R.E., **"TESTS ON A 120-FT-SPAN PRESTRESSED CONCRETE BEAM"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.86, NO.ST9, SEPTEMBER 1960.

This paper reports on a test to failure that was done on a 120 ft. span prestressed concrete beam. The tests showed that the design assumptions regarding the loss due to friction on stressing and the loss of prestress due to creep, shrinkage and relaxation were perfectly satisfactory. The behavior of the beam within the working-load range was excellent and agreed with the predicted behavior.

At ultimate load the beam failed by crushing of the concrete in the top flange at a deflection of 20". The calculated ultimate load was 6% less than actual failing load. Thereby, vindicating the assumptions by which the ultimate load calculations were based.

16. BEAL,D.B., **"PERFORMANCE OF CONCRETE BRIDGES REINFORCED WITH HIGH STRENGTH STEEL: FIRST INTERIM REPORT"**, RESEARCH REPORT 69-16, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, 1970.

This report explains the live load and long term dead load performance of two bridges in New York. The report is primarily focused on long term deflections, shrinkage cracks, etc.

17. BEAL,D.B., **"REINFORCEMENT OF CONCRETE BRIDGE DECKS"**, RESEARCH REPORT 105, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, JULY 1983.

Laboratory tests of reduced scale bridge decks and field tests of full-scale decks were performed to demonstrate the strength and serviceability of isotropic reinforcement.

Service load stresses were shown to be substantially less than the values predicted by AASHTO flexural design requirements. Limited results are available for the models tested to failure and the prototypes tested.

18. BEAL,D.B., **"STRENGTH OF CONCRETE BRIDGE DECKS"**, RESEARCH REPORT 89, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, JULY 1981.

Two reinforced concrete bridge deck models were constructed to study behavior under working loads and failure.The first model was constructed in accordance with current standard bridge deck design. Second model was constructed with three different values of isotropic reinforcement, one of which represented Ontario practice.

Results showed that for either type of reinforcement service load bending moments were 40-65% of those predicted by flexural theory. Failures were by punching shear rather than flexure and occurred at loads six times larger than design.

19. BEAL,D.B., **"LOAD CAPACITY OF A JACK-ARCH BRIDGE"**, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, RESEARCH REPORT 129, FINAL REPORT PROJECT 156-2, NEW YORK STATE DOT, ALBANY, NEW YORK, DECEMBER 1985.

A 76 year old jack-arch bridge was tested to failure to obtain information on load capacity and degree of composite action between the steel beams and concrete deck.

The 39-ft-test span consisted of six 24-in deep I-beams spaced at 36 in. Instrumentation consisted of electrical-resistance strain gages on both flanges at midspan, end-rotation measurement devices at the ends of two beams, and deflectometers at midspan. The bridge was loaded to produce a 6 ft. region of constant moment at the center of span.

The report gives detailed information about instrumentation and geometry of the structure. The results are given in both graphic and tabular form of load-deflection curves. The transverse deflection patterns are also shown. The end rotation versus line load curves are also presented along with the analytical and experimental moments and their lateral distribution.

20. BEAL,D.B., **"FAILURE TEST OF A JACK-ARCH BRIDGE"**, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, RESEARCH REPORT 110, INTERIM REPORT PROJECT 156-2, NEW YORK STATE DOT, ALBANY, NEW YORK, 1984.

A 47-ft. jack-arch bridge was loaded to failure to determine the degree of composite action between the steel beams and the concrete encasement. Measurements included strain in the top and bottom flanges of the beams, midspan deflections of all beams and end rotation of two beams. The results showed that at service loads the "simple supports" acted like fixed, and end restrains dissipated with increasing load.

21. BEAL,D.B., **"DESTRUCTIVE TESTING OF A REINFORCED CONCRETE T-BEAM BRIDGE"**, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, RESEARCH REPORT 100, NEW YORK STATE DOT, ALBANY, NEW YORK, 1982.

This paper reports on test results of a reinforced concrete T-beam bridge to evaluate the consequences of concrete deterioration on load capacity. The condition of the bridge was rated 2.5 on a scale from 1 (potentially hazardous) to 7 (new condition). The concrete deck was highly fractured throughout and the cement paste severely deteriorated locally. Tension rebars exposed by concrete spalling had lost about 1-2% of cross sectional area.

This study concluded that the structure tested showed no reductions in load capacity despite its apparently heavily deteriorated condition. Based on theoretical arguments, it is concluded that deterioration sufficient for substantial reduction of the capacity of a structure would be manifested in a local collapse, and that overall failure of reinforced-concrete T-beam bridges need not be a concern. A strategy for load rating has also been outlined in this paper based on the conclusions drawn in this report.

22. BEAL,D.B., KISSANE,R.J., **"FIELD TESTING OF HORIZONTALLY CURVED STEEL GIRDER BRIDGES: FIRST INTERIM REPORT"**, RESEARCH REPORT 69-11, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, APRIL 1971.

This report describes the testing of a horizontally curved steel girder bridge. The report includes a short description of instrumentation, test vehicle details and loading positions. The bridge was instrumented before the concrete deck was poured.

Test results are presented as stresses at different parts (webs, flanges etc..) of girders. Also presented are distributions of stresses in transverse direction. Deflections at different cross-sections are also presented.

A comparison of test results and the theoretical solutions show that they are highly correlated for bending moments, but there are big discrepancies for deflection values.

23. BEAL,D.B., KISSANE,R.J., **"FIELD TESTING OF HORIZONTALLY CURVED STEEL GIRDER BRIDGES: SECOND INTERIM REPORT"**, RESEARCH REPORT 69-11, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, OCTOBER 1971.

A horizontally curved steel girder bridge of span 95 feet and radius of curvature of 162 ft. was instrumented during construction.

Report contains a detailed description of instrumentation, which consisted of strain gages, linear potentiometers, and thermocouples. An automatic data acquisition system was employed to record the data from the transducers.

First stage of the testing was the determination of the effects of dead loads. Curves showing the distribution of stresses and deflections among the girders are presented.

Two types of static live loadings were used in the test. First to determine the transverse load distribution and maximum bending stress, loading was placed accordingly. Second, load was applied directly over two girders.

The results of the live load tests are presented graphically as transverse distribution curves. The test results compared fairly well with the theoretical solutions with some exceptions. Also a comparison of the test results with a 1:8.33 model tested in Syracuse University are shown.

24. BOTZLER,P.W., COLVILLE,J., **"CONTINUOUS COMPOSITE-BRIDGE MODEL TESTS"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.105, NO.ST9, SEPTEMBER 1979, PP. 1741-1755.

This paper presents the results of ultimate load tests on two continuous-span composite slab-girder bridge models. One model was a three-girder two-span structure and the other was a three-girder three-span structure. Models were tested to failure with a single concentrated load applied over the center girder. The tests were done to determine the variations in both the distribution of moment throughout the structures and the effective widths of slab acting with each girder as the load is increased to failure.

A finite difference analysis that model the system as an orthotropic plate gives acceptable agreement with the test results of both bridge models. It was concluded that effective widths and distribution factors at failure loads are significantly different from values obtained at service loads.

24A. BRYSON,J.O., MATHEY,R.G., **"SURFACE CONDITION EFFECTS ON BOND STRENGTH OF STEEL BEAMS EMBEDDED IN CONCRETE"**, JOURNAL OF THE AMERICAN CONCRETE INSTITUTE, VOL.59, NO.3, MARCH 1962.

Wide flange structural steel beams with different surface conditions were embedded in concrete and subjected to push-out tests to determine the effect of surface condition on the bond between concrete and steel. The surfaces of the embedded steel beams were either freshly sandblasted, sandblasted and allowed to rust, or left with normal rust and mill scale.

The steel beams with a sandblasted surface, and those with a sandblasted surface which was allowed to rust, developed considerably higher ultimate bond stresses than beams with normal rust and mill scale. However, at a free-end slip of 0.001 in. there was no significant difference in the bond stress for all three types of surface conditions.

25. BUCKLE,I.G., DICKSON,A.R., PHILLIPS,M.H., **"ULTIMATE STRENGTH OF THREE REINFORCED CONCRETE BRIDGES"**, INTERNATIONAL CONFERENCE ON SHORT AND MEDIUM SPAN BRIDGES, TORONTO, 1982.

This report details the results of three bridges tested to failure in New Zealand. Data is presented reasonably well. Load-Deflection curves for the three bridges are presented.

The destructive testing of three reinforced concrete highway bridges, recently made redundant by road realignment, is summarized. The procedure used to test the bridges to ultimate conditions is described and load capacities of about twenty times Class 1 axle loads are reported for all structures. Analyses based on conventional ultimate strength theory can account for only two-thirds of these ultimate loads and then only if second order effects are included. A non-linear finite element computer program has been developed and was used to analyze one of these structures. It is suggested that compressive membrane action, which is automatically modeled in the finite element solution, plays a significant role in the enhancement of load capacity.

The paper concludes that a more sophisticated approach to the assessment of bridge load capacity is necessary if realistic estimates of actual strength are to be made. Limited experience with non-linear finite element program suggests one such approach. If used with care, some relief of the bridge replacement program can be expected.

26. BURDETTE,E.G., GOODPASTURE,D.W, **"FULL SCALE BRIDGE TESTING: AN EVALUATION OF BRIDGE DESIGN CRITERIA"**, UNIVERSITY OF TENNESSEE, DECEMBER 1971.

Four deck girder highway bridges in Tennessee were tested under the actions of three types of loading:

(1) Vibratory loading induced by FHWA vibration generating equipment.

(2) Rolling loads simulating an HS20 loading with additional loads up to 132,000 pounds.

(3) Static tests to failure.

27. BYRD, TALLAMY, MCDONALD, LEWIS, **"FORECASTING SAFE LOAD CARRYING CAPACITY AND RATING BRIDGES"**, FHWA RESEARCH PROJECT DTFH61-84-C-00080, 1985.

The research centers on the methodology used to evaluate commonly occurring damage such as corrosion, impact (wrecks,etc.) and fatigue to existing bridge structures. Recommendations concerning how to properly

access damage, and repair procedures to refurbish existing structures will be presented at a later date. An annotated bibliography is also included in the report.

28. CAMPBELL,J.J., **"PROGRAM TO ACHIEVE UNIFORM RATINGS IN BRIDGE INSPECTION"**, PROCEEDINGS OF SECOND ANNUAL INTERNATIONAL BRIDGE CONFERENCE, PITTSBURGH, PENNSYLVANIA, JUNE 1985, PP. 90-96.

This paper focuses on the importance of collecting accurate and uniform information for the bridge inventory record system. The writer suggested a bridge condition rating enhancement which have been reviewed and approved for use by FHWA and the Pennsylvania D.O.T.

The bridge condition rating includes rating steel bridges and steel structural elements, and also reinforced concrete structures and reinforced concrete structural elements. The condition rating goes from 0 (critical condition - possible immediate collapse) to 9 (new condition).

29. CAMPBELL,T.I., **"THE McCOWAN BRIDGE TEST: PROTOTYPE FOR VOIDED POSTTENSIONED CONCRETE BRIDGE DECKS"**, RR194, ENGINEERING RESEARCH AND DEVELOPMENT DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DECEMBER 1974.

This report describes the field tests carried out on a three span, continuous, post-tensioned concrete deck which was cast in-situ and contained longitudinal circular voids. The three spans were 118 ft.-148 ft.-118 ft. and were 58.5 ft. wide.

The report is primarily concerned with the cracks formed by post tensioning and their propagation. Static and dynamic live load tests were performed.

The wide beam analogy seemed to yield results reasonably close to finite element analysis and test results.

30. CARPENTER,J.E., MAGURA,D.D., **"STRUCTURAL MODEL TESTING - LOAD DISTRIBUTION IN CONCRETE I-BEAM BRIDGES"**, JOURNAL OF PCA, VOL.7, NO.3, SEPTEMBER 1965, PP. 32-48.

This paper presents the results of tests conducted on four small-scale Plexiglass models of prestressed concrete highway bridges continuous over two-spans. The distribution of a concentrated load to the various girders was measured for different width-to-span ratios and several arrangements of interior diaphragms. Results were found to conform closely to those predicted by elastic theory.

The effect of placing the AASHO H20-S16-44 loading on the various test bridges, calculated from model test data, is compared with the AASHO specifications and calculations based on the Guyon-Massonnet elastic theory. The Guyon-Massonnet theory was found to be a good predictor of the deflections under load of the model bridges, and presumably those of the prototypes.

30A. CAUGHEY,R.A., **"COMPOSITE BEAMS OF CONCRETE AND STRUCTURAL STEEL"**, PROCEEDINGS, 41ST ANNUAL MEETING, IOWA ENGINEERING SOCIETY, 1929, PP.96-104.

Six composite T-beams were studied. From his results and tests published before 1929, the author concluded that composite T-beams without mechanical connectors could be designed safely. An allowable bond stress of $0.03f_c'$ was suggested.

31. CHEN,C.H., VANHORN,D.A., **"SLAB BEHAVIOR OF A PRESTRESSED CONCRETE I-BEAM BRIDGE - LEHIGHTON BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 349.5, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, JULY 1971.

This paper presents the experimental results from the field test of the deck slab of a prestressed concrete I-beam bridge superstructure. Tests were conducted with a simulated HS20-44 vehicle moving at speeds ranging from 2-10 mph., and moving across a midspan ramp at a speed of 10 mph. In general, it was concluded that there was very little cracking of the slab under typical live load design conditions.

32. CHEN,C.H., VANHORN,D.A., **"STATIC AND DYNAMIC FLEXURAL BEHAVIOR OF A PRESTRESSED CONCRETE I-BEAM BRIDGE - BARTONSVILLE BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 349.2, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, JANUARY 1971.

This paper presents the results of testing done on an existing ten-span I-beam bridge. The objectives of the test were:

1. To obtain information on lateral load distribution of design vehicle loading at crawl speed.
2. To establish the amplification characteristics of crawl-run response under dynamic and controlled impact loading.
3. To compare the behavior to that of a box girder bridge previously tested.

It was found that the experimental distribution factors for the interior girders were near the design value, while for the exterior girders, experimental values were greater than the design values. It was also demonstrated that the curb and parapet sections substantially stiffened the exterior beams, thus significantly affecting the load distribution characteristics.

33. CHEN,Y.L., VANHORN,D.A., **"STRUCTURAL BEHAVIOR OF A PRESTRESSED CONCRETE BOX-BEAM BRIDGE - HAZLETON BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 315A.1, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, DECEMBER 1970.

This paper describes the field testing of an in-service beam-slab highway bridge. A test load vehicle, simulating an AASHO HS20-44 design vehicle was used to produce the live-load effects in the structure. The objectives of the test were to investigate the structural response of the bridge to:

1. Test vehicle traveling at constant speed (2-60 mph.)
2. An impact test in which the test vehicle passed over a 2" high ramp at 10 mph.
3. Provide additional information on the lateral distribution of static vehicle loading.

The development of distribution factors from the experimental data reflected the inaccuracy of the design values for spread box-beam superstructures. A suggestion was made to consider the strength contributions of the curb and parapets for a more realistic evaluation.

34. CORLEY,W.G., **"ROTATIONAL CAPACITY OF REINFORCED CONCRETE BEAMS"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.92, NO.ST5, OCTOBER 1966, PP. 121-146.

This paper reports on the results of a study of the moment-rotation capacity of reinforced -concrete beams in the region of a peak in the moment diagram. All tests were conducted on simple span beams loaded with a concentrated load at midspan, to approximate the conditions near supports and near points of load application in continuous beams. The effects of moment gradient, specimen size, confinement of the concrete in compression, and variations in the amount of tension reinforcement were studied. All beams in these tests were under-reinforced and failed by crushing of the concrete after the tension reinforcement had yielded.

35. CROCE,C.A., BEAL,D.B., **"LIVE LOAD STRESSES ON A STRAIGHT BOX GIRDER BRIDGE"**, RESEARCH REPORT 19, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, 1973.

The two span continuous bridge investigated consisted of two trapezoidal steel box girders with a composite monolithic reinforced concrete deck slab. The span lengths are 133 and 164 ft and there is a skew angle of 46 degrees.

The bridge was designed with a load distribution factor (AASHTO) of 2.933 (three lanes). The results obtained from the tests yielded distribution factors between 2.59 and 3.08.

36. CRONK,D.M., ROGERS,D.H.,JR., **"FIELD STUDY OF A PREDEFLECTED STEEL-CONCRETE COMPOSITE BRIDGE: FINAL REPORT"**, RESEARCH REPORT 23, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, 1974.

This report is a continuation of the interim report. Emphasis being mostly on the long term shrinkage, creep, and temperature behavior.

Report concludes that the theoretical methods used in predicting the behavior were reasonably good.

37. CSAGOLY,P.F., HOLOWKA,M., **"CRACKING OF VOIDED POST-TENSIONED CONCRETE BRIDGE DECKS"**, RESEARCH REPORT 193, RESEARCH AND DEVELOPMENT DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, JANUARY 1975.

The report examines the problem of cracking in voided, post tensioned concrete bridge decks.

Study includes monitoring of deformations and temperature variations of a prototype bridge. Acrylic model of two typical prototype bridges were tested. An automated finite element computer program was written. Long term testing of voided micro-concrete models was performed. The prototype structure was tested with the MTC bridge testing vehicle for static and dynamic live loads. The test results agreed with design values and wide beam approximation gave a mean value of the finite element results for longitudinal bending caused by live load.

Report also describes the acrylic model studies for the examination of the elastic response of the structure.

38. CSAGOLY,P.F., BAKHT,B., **"LATERAL BUCKLING OF PONY TRUSS BRIDGES"**, TRANSPORTATION RESEARCH REPORT 607, TRANSPORTATION RESEARCH BOARD, WASHINGTON D.C., 1976.

This paper presents a method for investigating the lateral stability of a pony truss bridge on a more rational basis than has been attempted in the past. The complex problem of lateral buckling of truss compression chords, which in the past has led to oversimplifying assumptions resulting in underestimation of the bridge strength, has been solved by a computer program based on a modified version of Bleich's method. Implementation of the method of analysis was only possible by use of a computer. The program is written in ANSI FORTRAN and is named LATBUK.

The method of analysis accounts for the interaction of the compression chord and the transverse portals and for the change of direction of the chord at the shoulder points. Comparison of the program results to those of model and full scale tests has proved the validity of the method, and can be used to check the load carrying capacity of pony truss bridges.

39. CSAGOLY,P.F., TAYLOR,R.J., **"A DEVELOPMENT PROGRAM FOR WOOD HIGHWAY BRIDGES"**, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, REPORT 79-SRR-7, PREPARED FOR THE 1979 RTAC ANNUAL CONFERENCE, 1979.

The report describes the general timber bridge types and their load carrying capacity determination.

It provides a list of timber bridges on which tests were performed by the Ontario Ministry of Transportation and Communications, or will be performed. These also include steel-wood composite structures and concrete-wood composite decks.

40. D'APICE,M.A., COOPER,P.B., **"STATIC BENDING TESTS ON LONGITUDINALLY STIFFENED PLATE GIRDERS"**, FRITZ ENGINEERING LABORATORY REPORT NO. 304.5, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, APRIL 1965.

This paper presents the results of static bending tests of five longitudinally stiffened plate girders. The experimental variables were the panel size and longitudinal stiffener size. The primary test objectives were:

1. To determine to what extent longitudinal stiffeners can contribute to the resistance of the web to vertical buckling of the compression flange.

2. To determine how the stress redistribution at loads above the theoretical web buckling load is affected by the presence of a longitudinal stiffener.

3. To determine to what extent lateral web deflections can be reduced by the use of a longitudinal stiffener.

The test setup, procedure and results are presented in tables and graphical illustrations. It is concluded that the longitudinal stiffeners were effective in retarding stress redistribution and in controlling web deflections, but for the stiffener sizes used in these tests, no significant increase in bending strength due to the presence of longitudinal stiffeners was observed.

41. DAVEY,N., **"TESTING OF HIGHWAY BRIDGES"**, INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERING (IABSE) PUBLICATIONS VOL.9, 1949.

The paper gives a very brief description of the tests run on masonry arch and cast iron girder highway bridges built in the 1700's and 1800's.

42. DAVIS,R.E., **"STRUCTURAL BEHAVIOR OF A SKEW, REINFORCED CONCRETE, BOX GIRDER BRIDGE MODEL"**, FHWA-CA-ST-4187-78-01, OFFICE OF STRUCTURES DESIGN, CALIFORNIA DOT, 1978.

A two span, continuous, reinforced concrete, box girder bridge, with supports skewed 45 degrees, was to be modeled at a scale of 1:2.82, instrumented and tested at the University of California, Berkeley, to assess anomalies in structural behavior by comparison with previously observed behavior of straight and curved models of the same scale, on orthogonal and radial supports, respectively. In particular, it is desirable to explore variations in support reactions from those observed for structures on normal supports and large dimunitions in longitudinal girder resisting moments evidenced by analysis with a finite element program, called CELL, by means of which the model was designed. Methods used in the model design are described in detail in this preliminary report.

42A. DEATHERAGE,J.H., **"INVESTIGATION OF VARIABLES AFFECTING BEAM-SLAB BRIDGE LOAD CAPACITY"**, PhD. DISSERTATION, UNIVERSITY OF TENNESSEE, KNOXVILLE, JUNE 1987.

The purpose of this research was to identify and investigate variables having a major influence on bridge load carrying capacity which would not normally be considered in conventional analysis techniques. The

ability to predict the load carrying capacity of beam-slab bridges is of vital interest to researchers, bridge design engineers, maintenance engineers, public servants, and the general public.

The ability to properly distribute applied loads to the primary structural members is of fundamental importance. Current design specifications and analysis techniques result in overly conservative estimates of load distribution to individual components. A Guyon-Massonet method has been developed to allow a practicing bridge engineer to more accurately distribute applied loads to the individual components of a beam-slab bridge system and thus improve the quality of structural analysis to develop better correlation with test results.

43. DECASTRO,E.S., KOSTEM,C.N., MERTZ,D.R., VANHORN,D.A., **"LIVE LOAD DISTRIBUTION IN SKEWED PRESTRESSED CONCRETE I-BEAM AND SPREAD BOX-BEAM BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 387.3, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, AUGUST 1979.

This paper presents an investigation on the effects of skew on the design moments and on the lateral distribution of statically applied vehicular loads on prestressed concrete spread box-beam bridge superstructures. The skew angles investigated were 90, 60, 45 and 30 degrees. It was observed that:

1. The load distribution factor decreased with decreasing angle of skew.
2. The reduction factor was largest at shorter span lengths for interior beams and at longer span lengths for exterior beams.
3. The bridge width-to-span ratio, the beam spacing-to-span ratio, and the skew angle sufficiently affect the magnitude of the percentage reduction factor.

Simplified equations for computing distribution factors for interior and exterior box girders were developed.

44. DECASTRO,E.S., KOSTEM,C.N., VANHORN,D.A., **"A PILOT STUDY OF FACTORS AFFECTING LIVE LOAD DISTRIBUTION IN PRESTRESSED CONCRETE BEAM-SLAB BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 387.4, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, AUGUST 1979.

This paper describes a very brief pilot study of the structural behavior of prestressed concrete beam-slab bridges, particularly live load distribution, as affected by: curb parapet sections, intra-span diaphragms and continuity over the supports in multi-span structures.

For simple span bridges, it was found that consideration of the longitudinal strength and stiffness of the curb-parapet sections yielded higher values of distribution factors for the exterior beams and lower values for interior beams. The effect of intra-span diaphragms was found to distribute more evenly the live load to the longitudinal beams. The midspan diaphragm was found to be more effective than other combinations considered. For multi-span bridges constructed with longitudinal continuity over the supports, the live load distribution was found to be similar to the distribution in simple span bridges of shorter span.

45. DICKERSON,B.L., **"RELIABILITY OF COMPOSITE ACTION IN STEEL-CONCRETE BEAMS"**, SPECIAL PROBLEMS, UNIVERSITY OF TENNESSEE, 1986.

This paper presents the results of a study to determine when composite action can be counted on in steel-concrete beams. Reports of tests on composite and non-composite sections were studied and reviewed. It was concluded that composite action may be counted on to ultimate if the shear connection provided is sufficient for full composite action as determined from current design criteria.

Although studies and tests have shown that non-composite beams often act compositely through the service load range, the shear connection (provided by natural bond and friction) is very unreliable. It was concluded that non-composite sections should not be counted on to act compositely.

46. DILGER,W., BEAUCHAMP,J.C., CHEUNG,M.S., GHALI,A., **"FIELD MEASUREMENTS OF MUSKWA RIVER BRIDGE"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, NOVEMBER 1981, PP.2147-2161.

This paper presents the results of field measurements performed on a two-lane steel-concrete composite bridge, continuous over five spans. The total length is about 1080 ft. Because of the extreme climatic conditions and relatively large span length (300'), it was decided to monitor the bridge and collect the performance data, during the construction of the deck slab and during the first few years in operation.

The most important finding in this study is the large temperature difference of 73 degree F between the concrete deck and the steel box exposed to the

sunlight. The writers recommended that differential thermal stresses be considered in the design of composite box girder bridges. Cracking on the concrete deck was attributed to :

i. Temperature developed in concrete deck shortly after casting;

ii. Sequence of casting;

iii. Shrinkage of deck concrete;

iv. Rapid heating of steel boxes exposed to direct sunlight.

The cracking of concrete deck resulted in a reduction of the stiffness of the structure. Strain distribution has been found to be approximately linear over the depth of the web plates and the width of the bottom plates.

47. DOUGLAS,W.J., VANHORN,D.A., **"LATERAL DISTRIBUTION OF STATIC LOADS IN A PRESTRESSED CONCRETE BOX-BEAM BRIDGE - DREHERSVILLE BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 315.1, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, AUGUST 1966.

This paper describes the field testing of a three-span simply supported bridge with a cast-in-place concrete deck supported by five precast prestressed concrete box girders. Primary objective of the test was to determine the lateral distribution of live load to the girders, and to evaluate various field test techniques for use in the following studies.

Results showed that distribution factors derived experimentally were substantially different from the design distribution factors. Test results also indicated that full composite action was developed between the bridge deck, curb and parapet.

48. EDMONDS,F.D., FULLARTON,D.H., **"STRAIN AND DEFLECTION MEASUREMENT - PAEKAKARIKI RAILWAY OVERBRIDGE"**, CENTRAL LABORATORIES REPORT NO. 5-77/3, GRACEFIELD, LOWER HUTT, NEW ZEALAND, 1977.

This paper summarizes the main beam strain and deflection measurements obtained during live load testing of the critical span of the Paekakariki railway overbridge, which is a reinforced concrete structure of 8 spans, 6 spans of 40 ft. and 2 of 35.3 ft. The work was carried out to provide experimental data to assist in the load rating of the bridge. Measurements were made for both static and dynamic live loading of the bridge span.

The site measurements were used to determine moment eccentricity factors for the main beams and to assess the effect of impact loading and continuity between the adjacent spans of the bridge. Using the site measurements as a basis for comparison, a procedure to calculate the input parameters for a finite element model of the bridge span was developed.

49. ELLEBY,H.A., SANDERS,W.W., KLAIBER,F.W., REEVES,M.D., **"SERVICE LOAD AND FATIGUE TESTS ON TRUSS BRIDGES"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.102, NO.ST12, DECEMBER 1976, PP.2285-2300.

This paper presents the results of service load tests on two truss bridges, namely the Hubby bridge and the Chestnut Ford bridge. The Hubby bridge composed of four modified Parker-type high truss simple spans, each 165 ft. long, while the Chestnut Ford bridge composed of four high-truss simple spans, with the test span of modified Pratt-type 150 ft. long. This report covers the service load tests on the two bridges as well as the supplementary tests, both static and fatigue, of eyebar members taken from the two bridges at the time of removal. The field test results of the service loading are compared with theoretical truss analyses.

50. FAN,H.M., HEINS,C.P., **"EFFECTIVE SLAB WIDTH OF SIMPLE SPAN COMPOSITE BRIDGES AT ULTIMATE LOAD"**, UNIVERSITY OF MARYLAND CIVIL ENGINEERING DEPARTMENT, REPORT NO. 57, INTERIM REPORT AW-120-3, THE ULTIMATE CAPACITY OF HIGHWAY BRIDGES, PART1-SIMPLE SPANS, 1974.

This paper presents a study to evaluate the effective width of simply supported composite bridges at ultimate load. An analytical method was developed by which the elastic and elasto-plastic deformations of such a system can be predicted. The resulting equations were solved by a computer program. This report is divided into two sections: Part A deals with the application of the analytical system while Part B deals with the theory in developing the analytical system. The analytical method treated the deck slab as an orthotropic plate and considers strain compatibility between the slab and girder.

Using the computer program, many typical two-lane composite bridges were analyzed. The effective widths at ultimate load were then determined and were found not to equal the effective widths at the elastic condition. The effective widths at ultimate for both interior and exterior girders are presented in the form of a general equation.

51. FLEEGE,E.J., McFARLIN,R.J., **"OVERLOAD DESIGN CONCEPT FOR GARFIELD AVENUE BRIDGE"**, INTERNATIONAL CONFERENCE ON SHORT AND MEDIUM SPAN BRIDGES, TORONTO, SESSION 7, 1982.

This paper presents an overload design concept which was developed in the design of the Garfield Avenue Bridge to enable the bridge of handling payloads of 2669 kN (300 tons). The Minnesota D.O.T. was requested to construct the bridge with carrying capacity of this order. Using historical data, a design overload concept consisting of "blocks" of uniform loads where each such block represents a group of axles was formulated. This design live load consists of two areas with uniform load of 0.525 ksf. Each of the two loads is 16 ft. by 50 ft., which are the dimensions of the twelve-axle transport vehicles which presently exist, and which appear to encompass all reasonable overload vehicles likely to be operating in the immediate future. Together with this design live load and a modified load factor design relationship of 1.3(DL + 1.15LL), the bridge will have the requested payload capacity. It is estimated that this overload design will increase the cost of the bridge by about 10%.

52. FORNEROD,M., **"LOAD AND DESTRUCTION TEST OF 160FT. GIRDER DESIGNED FOR FIRST PRESTRESSED CONCRETE BRIDGE IN U.S."**, INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERING (IABSE) PUBLICATIONS, VOL. 10, 1950.

This paper reports on the testing to destruction of a typical 160 ft. girder. The test was not only a requirement of the specifications but also served to demonstrate the conservative margin of safety and the behavior of the girder under working and failure loads. The working live load was specified as a standard H20-44 load pattern including an addition for impact of 17%.

The results showed that present methods of design are adequate and on the safe side. Results of the test also emphasized the importance to differentiate clearly between safety against cracking and safety against failure. Failure took place at a total midspan moment of 20,800 kip-ft. which is 2.75 times the total working load moment.

53. FULLARTON,D.H., EDMONDS,F.D., **"DESTRUCTIVE TESTING OF THE MANGATEWEKA STREAM BRIDGE"**, CENTRAL LABORATORIES REPORT NO. 5-78/1, CENTRAL LABORATORIES, GRACEFIELD, LOWER HUTT, NEW ZEALAND, 1977.

This paper discusses the elastic and post yield live load response of a 9.6 m (31.5 ft.) reinforced concrete T-beam bridge. The tests are carried out in 3 parts:

1. The elastic response of the bridge to live load was assessed by measuring the static strains and deflections produced by a 10 ton truck. A finite element model was also done in comparison.
2. Jack loading the bridge to failure.
3. Proof loading test on the bridge deck and a comparison of the recorded deck slab response with the theoretical deflections.

The analyses of the bridge using a finite element model takes into account two additional factors:

1. At level of loading imposed by the truck, bridge exhibited almost full end fixity.
2. The curb had a significant effect on the outer T-beams.

The results produced by the finite element analyses provided close comparison with recorded steel strains and span deflections.

The test results are discussed with reference to the posting and overweight load classification procedures and a proposal for proof load testing of similarly constructed bridges is made in this report.

54. GAMBLE,W., **"TESTS OF PRESTRESSED CONCRETE LONG-SEGMENT BRIDGE GIRDERS"**, INTERNATIONAL CONFERENCE ON SHORT AND MEDIUM SPAN BRIDGES, TORONTO, SESSION 4, 1982.

This paper describes the tests done on two two-span continuous bridge girders. Each girder consisted of three long precast segments which were joined end-to-end by post tensioning after cast-in-place composite deck and splice region concrete had reached the required strengths. One girder was full scale, with two spans of 37.8 m or 124 ft. each. The second was a reduced-scale structure having spans of 11.3 m or 37 ft. each. Each girder was subjected to a series of loadings, to successively higher loads.

The tests established that joints between girder segments can be designed and built to transfer substantial flexural and shear forces.

55. GANGARAO,H.V.S., **"SURVEY OF FIELD AND LABORATORY TESTS ON BRIDGE SYSTEMS"**, TRANSPORTATION RESEARCH RECORD 645, TRANSPORTATION RESEARCH BOARD, WASHINGTON D.C., 1977, PP.10-15.

This paper reports on field and laboratory tests which were conducted to study the behavior of several short span bridge systems: orthotropic deck; composite box girder; composite U-beam superstructure; precast, prestressed concrete deck planks; and concrete box girder.

Test results for orthotropic bridge systems revealed that dual tire stresses are less severe than those caused by single tires and that the impact factor for girders was about one-third of the suggested AASHO value although the local effects on the deck and floor beams reached about 30% of equivalent static load.

Precast, prestressed concrete slab units appeared to lend themselves to renovation of commonly built deck-stringer bridges. However, a special joint with a flat center portion between the precast units was found to be essential to preventing spalling during posttensioning operations.

Tests of composite and all-concrete box-girder systems indicated a better transverse load distribution relative to the other systems discussed, and were found to be durable and economical.

The concrete U-beam girder system with cast-in-place deck provided complete composite action and behaved as a box system, but discontinued for economic reasons.

The experimental results yielded better transverse load distributions for deck length-to-width ratios of the order of 1:2. The transverse distribution was also found to be a function of the number, the type, and the positioning of loads.

Exponential variation of the transverse load distribution factor with the flexural parameter (lambda) is tentatively suggested for interior girders, and a constant distribution factor of 2.13 is recommended for exterior girders.

56. GEMENY,A.L., **"REPORT ON LOADING TESTS OF A REINFORCED CONCRETE ARCH BRIDGE OVER THE YADKIN RIVER IN NORTH CAROLINA"**, PUBLIC ROADS VOL.9, NO.10, 1929.

This report presents the results of loading tests done on Yadkin River Bridge, which consists of three 2-rib open-spandrel arch spans of 146'3" clear span and 28'3" rise with seven 42'6" deck-girder approach spans at each end. The data obtained appeared to justify the following points:

1. The action of an arch rib, when free from the restraining effect of the superstructure and supported by practically immovable piers, conforms closely to the theory of elastic structures.
2. The observed compressive stress in the concrete at any section of the rib checks the computed stress more closely when it is assumed that the concrete takes tension.
3. The observed tension in the steel was, in general, less than that computed by assuming the concrete to take no tension.
4. The superstructure in an open-spandrel rib arch greatly reduces the deformation of the rib.
5. A quantitative determination of the effect of the superstructure on the arch may be made by the use of the Beggs deformeter gauges on an elastic model of celluloid, or other material, if all members are connected in a definite way.

57. GOSBELL,K.B., STEVENS,L.K., **"TEST LOADING OF A FULL SCALE BRIDGE"**, PROCEEDINGS OF THE FOURTH CONFERENCE OF THE AUSTRALIAN ROAD RESEARCH BOARD, VOL.4, PART 2, 1968, PP. 2018-2041.

The bridge consisted of seven prestressed girders at 4'-9" o.c. with curbs and handrails. The objectives of the test program were as follows:

1. Obtain distribution coefficients and moments in the elastic region.
2. Observe the effect on the distribution coefficients in the elastic range.
3. Check the efficiency of the central diaphragm in distributing loads.
4. Establish the contribution of the handrails and curbs over the complete load range.
5. Study the behavior at ultimate load and determine the mode of failure.
6. Study the local effect of wheel and axle loads on the deck slab.

The data was presented in a clear and concise manner and was reasonably easy to understand.

ULTIMATE LOAD TEST:

The bridge was loaded eccentrically to simulate single lane overload condition. The bridge was loaded to 300 kips (approx. 3Pcr) and deflections of almost 5 inches were measured. A good P-Delta curve (well past yield) was presented. The author concluded that "remarkably little variation occurs in the distribution coefficients even after extensive cracking had

developed at loads several times the initial cracking load. The use of distribution coefficients derived for elastic action would therefore appear to be reasonable for approximate estimation of post cracking behavior." i.e. wide beam theory does not hold true for single lane simulated loads.

58. GOSSARD,M.L., SIESS,C.P., NEWMARK,N.M., GOODMAN,L.E., **"STUDIES OF HIGHWAY SKEW SLAB-BRIDGES WITH CURBS"**, UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION BULLETIN NO. 386, 1950.

This paper reports on four skew slab-bridge models of reinforced concrete. Three of the models had 45 deg. angles of skew, 1/2 scale, with span lengths of 9 ft 9 in. The fourth model had a 60 deg. angle of skew, 1/5 scale, with normal span of 5 ft 11 in. The amount and arrangement of steel reinforcement varied from bridge to bridge. All bridges were of two-lane capacity, and had integrally cast curbs. The results show:

1. The theory and experiments are in good qualitative agreement for bridges in both uncracked and cracked conditions.
2. The quantitative agreement of the theoretical and measured strains is fair for uncracked structures, poor for cracked structures.
3. Effects of varying amounts and arrangements of reinforcing on the strains are detectable and can be qualitatively explained.
4. Initial failure in the 45 deg. skew bridges appears as yielding of the bottom spanwise steel at the center of the slabs, and in the 60 deg. skew bridge, as yielding of the top transverse slab steel in an obtuse corner of the bridge.
5. Ultimate loads range from 1.5-2.5 times the loads at initial failure.

59. GUILFORD,A.A., VANHORN,D.A., **"LATERAL DISTRIBUTION OF DYNAMIC LOADS IN A PRESTRESSED CONCRETE BOX-BEAM BRIDGE - DREHERSVILLE BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 315.2, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, FEBRUARY 1967.

This paper describes the field testing of a two-lane beam-slab highway bridge consisting of a reinforced concrete deck supported by five precast prestressed concrete box girders. The report was centered on the effect of vehicle speed on the lateral distribution of live loads, and on the magnification of crawl-run characteristics. It was found that increases in moment coefficient over crawl-run values were generally less than the value of the impact factor (50/L+125) used in the design of the structure. The differences were greater for the interior girders than for the exterior girders. The magnitudes of the distribution coefficient were relatively insensitive to the speed of the load vehicle. Crawl-run tests yielded greater distribution factors.

60. GUILFORD,A.A., VANHORN,D.A., **"LATERAL DISTRIBUTION OF VEHICULAR LOADS IN A PRESTRESSED CONCRETE BOX BEAM BRIDGE - BERWICK BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 315.4, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, OCTOBER 1967.

This paper describes the field testing of a spread box-beam bridge in order to evaluate the current design procedures for the lateral distribution of live load in this type of bridge, and to develop a new procedure which better represents the actual behavior of the structure. The test bridge consisted of four hollow prestressed concrete box girders, which were 48" wide by 39" deep, a composite reinforced concrete cast-in-place slab, and cast-in-place curbs and parapets. The test span was 65 ft. 3 in.

On this bridge, the distribution factors did not vary significantly between cross-sections. The same was true of the ratios of the experimental moment to design moment. For interior girders, the experimental distribution factor was considerably less than the design distribution factor, while for exterior girders, the experimental values were greater than the design values. It was found desirable to include the effects of curbs and parapets in future design procedures.

61. GUILFORD,A.A., VANHORN,D.A., **"LATERAL DISTRIBUTION OF VEHICULAR LOADS IN A PRESTRESSED CONCRETE BOX-BEAM BRIDGE - WHITE HAVEN BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 315.7, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, AUGUST 1968.

This paper describes the field testing of a prestressed concrete spread box girder bridge consisting of four hollow prestressed concrete box girders, a composite, cast-in-place reinforced concrete slab, and cast-in-place concrete curb and parapet sections. The primary test objective was to experimentally determine the lateral distribution of vehicular loads on this type of bridge.

The results showed that the experimentally based distribution factors were less than the design value for interior girders but significantly greater than the

design value for exterior girders. This increase in stiffness of the exterior girders resulted from the strength contribution of the curb and parapet sections.

61A. GUSTAFSON,W.C., WRIGHT,R.N., **"ANALYSIS OF SKEWED COMPOSITE GIRDER BRIDGES"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.94, NO.ST4, APRIL 1968, PP. 919-941.

The object of this report is to illustrate with a skewed composite girder bridge how a finite element analysis can account for the eccentricity of a girder with respect to the slab. It was stated that for a bridge of this type, the largest decrease in moment was for skew angles greater than 45 degrees. However, this decrease in moment was not particularly significant.

62. GUTKOWSKI,R.M., WILLIAMSON,T.G., **"TIMBER BRIDGES: STATE-OF-THE-ART"**, JOURNAL OF STRUCTURAL ENGINEERING, ASCE, VOL.109, NO.9, SEPTEMBER 1983, PP. 2175-2191.

This paper presents some of the significant design advancements during the past several decades related to the use of wood as a highway bridge construction material. Factors which have contributed to the renewed use of wood in the field of bridge construction include the development of new wood bridge system concepts, advancements in timber bridge design and analysis techniques and the consequences of the need to conserve natural resources. Wood's high strength to weight ratio, ease of fabrication and installation and natural renewability as a resource make it a highly viable material for consideration in bridge construction.

To illustrate the applicability of Press-lam to highway bridge construction, a bridge consisting of Press-lam stringers and deck panels was constructed. After three years, the bridge condition continued to be excellent. A series of full scale static tests to determine the adequacy of two different types of timber traffic railing designs proved them to be very strong and yet retain sufficient flexibility.

62A. GUYON,Y., **"CALCUL DES PONTS LARGE A POUTRES MULTIPLES SOLIDARISES PAR DES ENTRETOISES"**, ANNALES DES PONTS ET CHAUSSES'ES, PARIS, SEPT.-OCT. 1946, PP.553-612.

This paper presents Guyon's load distribution theory, where one of the important assumptions of Guyon is that no torsional resistance is assumed in the analysis. A Fourier Series is used for the solution of the partial differential equations.

63. HALL,J.C., KOSTEM,C.N., **"INELASTIC ANALYSIS OF STEEL MULTI-GIRDER HIGHWAY BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 435.1, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, 1980.

This paper presents a methodology developed to predict the elastic and inelastic response of highway bridge superstructures. Simple span or continuous multi-girder bridges with steel girders and reinforced concrete deck are considered. Inelastic behavior of the bridge is modeled through the use of nonlinear stress strain curves for concrete, reinforcing steel and structural steel. Initiation of the damage to the superstructure in the form of cracking or crushing of concrete and yielding of the steel is detected, progression of damage is monitored, and load versus deformation, and damage to the bridge, is developed until the structure collapse.

The developed method and the corresponding computer program BOVAS are designed to predict the overload response of the types of bridges described above.

64. HEINS,C.P., **"INFLUENCE OF BRACING ON LOAD DISTRIBUTION OF BRIDGES"**, INTERNATIONAL CONFERENCE ON SHORT AND MEDIUM SPAN BRIDGES, TORONTO, SESSION 5, 1982.

This paper presents a series of formulas, which can be used in direct design, representing the load redistribution (wind and truck loading) on braced and unbraced, straight and curved multi I-beam bridges. The paper also summarizes the effectiveness of bottom lateral bracing in multi-girder bridges, in conjunction with the cross diaphragms, although analytical confirmation has not been made to date.

The results are given in terms of a series of design equations for use in evaluating the wind load stresses in the bottom flanges and live load distribution factors for braced curved girders.

65. HEINS,C.P., KATO,H., **"LOAD REDISTRIBUTION OF CRACKED GIRDERS"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.108, NO.ST8, AUGUST 1982, PP.1909-1915.

This research is primarily an investigation to demonstrate that lateral bracing creates a redundancy in the structure and allows for redistribution of loads in a cracked or yielded girder. A mathematical model consisting of two girders was analyzed for spans of 120 feet and 180 feet. Five different finite element models were used to analyze the following conditions:

1. Two girders - unbraced - uncracked

2. Two girders - one cracked - unbraced
3. Two girders - one cracked - braced

The finite element model were as follows: -

1. Space frame elements
2. 3-D shell elements
3. 3-D shell elements (2x elements in case 2)
4. 3-D shell elements (8x elements in case 2)
5. 2-D plane elements (same no. of elements as case 4)

Conclusions were that lateral bracing definitely creates redundancy allowing for redistribution of loads. No attempt is made to quantify amount of redistribution from cracked to uncracked girder.

66. HEINS,C.P., HOLLIDAY,R.O., YOO,C.H., **"ULTIMATE LOAD RESPONSE OF A STEEL I-BEAM COMPOSITE MULTI-GIRDER SIMPLE SPAN BRIDGE MODEL"**, UNIVERSITY OF MARYLAND CIVIL ENGINEERING DEPARTMENT, REPORT NO. 54, MARCH 1974.

This paper examines the response of a multi-girder composite bridge model and to correlate the experimental ultimate load to the value predicted by an analytical technique.

The elastic, elastic-plastic, and fully plastic response of the model is presented in terms of deflections and strains in the model. These functions are also compared to the analytical results. It is observed that for loading configuration where little plate action of the slab is involved, the mathematical model is an adequate predictor of this system's response. But wherein the plate action of the slab becomes important, the mathematical model is a conservative predictor of the system's response.

However, the resulting comparison indicates that the analytical technique is an "accurate" predictor of the ultimate load. Thus, the use of this analytical technique should provide reasonable results in parametric studies.

67. HIGHWAY RESEARCH BOARD, **"THE AASHO ROAD TEST: REPORT 4 - BRIDGE RESEARCH"**, HIGHWAY RESEARCH BOARD, SPECIAL REPORT 61D, 1962.

This paper reports on a series of case studies intended to yield information on the behavior, under vehicular traffic causing overstress, of several types of beam and slab bridges. Eighteen test bridges were included in the study. Each bridge was a simple span structure consisting of three beams and a reinforced concrete deck. Eight bridges had steel beams, four had precast-prestressed high strength concrete beams. Beams for two bridges were post-tensioned and four reinforced concrete bridges were of cast-in-place T-beam construction.

Five types of tests were conducted. The principal tests were with the behavior and life of the bridges under repeated high overstress, with the ultimate strength of the bridges, and with dynamic effects of moving vehicles.

In general, agreement between the theory and experiment was hampered by a large number of uncertainties involved in the experimentally determined parameters, by experimental uncertainties concerning the data forming the basis of comparisons, and by certain limitations of the computer program used to obtain the theoretical solutions. However, many important findings were obtained from these experiments.

68. HIGHWAY RESEARCH LABORATORY, **"REPORT ON 19 FT. PRECAST BRIDGE SLAB TESTS"**, HIGHWAY RESEARCH LABORATORY, MISSISSIPPI STATE COLLEGE, 1954.

This paper presents the results of a series of tests done on a 19' precast bridge slab. The testing consists of:

1. Two keyway slabs with grout key in place.
2. Ultimate strength of 4.5" slab between girders of 19' precast bridge slabs.
3. Single 19' precast bridge slab loaded at midspan and 7.5" from one edge.
4. Ultimate load test for shear in girder of 19' precast bridge slab.

A summary of results was presented for each of the tests done.

69. HILTON,M.H., ICHTER,L.L., **"AN INVESTIGATION OF THE LOAD DISTRIBUTION ON A TIMBER DECK-STEEL GIRDER BRIDGE"**, VIRGINIA HIGHWAY AND TRANSPORTATION RESEARCH COUNCIL, VHTRC 76-R30, 1975.

This paper presents an investigation of the load distribution on a 48.5 ft. span timber deck-steel girder bridge under two conditions. The first condition was concerned with the load distribution when the timber deck fasteners were tight and the second condition involved investigating the load distribution when the fasteners were loosened in several stages.

It was concluded that the live load stresses in the girders were of the same general order of magnitude and that the lateral load distribution was generally the same whether the deck plank fasteners were loose or

tight. The load distribution factor currently used in Virginia was found to be too high for the interior girders, while slightly low for the exterior girders. Recommendations were made for improvement on better load distribution factors for this type of bridge.

70. HILTON,M.H., ICHTER,L.L., TAYLOR,D.W., **"LOAD DISTRIBUTION ON A TIMBER-DECK AND STEEL-GIRDER BRIDGE"**, TRANSPORTATION RESEARCH RECORD 645, TRANSPORTATION RESEARCH BOARD, WASHINGTON D.C., 1977, PP. 20-22.

This paper reports on a test which deals with the load distribution on an inservice bridge with a timber deck and steel girder. The test bridge was a 23 ft. wide by 48.5 ft. long simple span structure that conforms to the Virginia standards for wooden floor-steel beam bridges designed for H20 loading.

The study determined the stresses in the steel girders that resulted from various loading sequences. Load distribution characteristics of the structure were determined under varying conditions with loosened floor fasteners. The study shows that loosening of the deck plank fasteners does not have a very significant effect on either the magnitude or the lateral distribution of the stresses.

The load distribution factor of S/4 (specified by AASHO) was found to be conservative in all cases for the interior girders. This study suggested a distribution factor for the interior girders of S/5 would be adequate for legal limits. The highest load distribution to interior girders was developed by loading both lanes of the two-lane bridge.

The load distribution factor determined for the exterior girders by proportioning the load as the reaction of a simple beam between the exterior and the first interior girders was found to be inadequate in some instances. An analysis of other loading positions in the area between the first and second girders suggests that the use of a distribution factor of S/5 would be more realistic than the current procedure used.

71. HOLOWKA,M., **"TESTING OF A TRAPEZOIDAL BOX GIRDER BRIDGE"**, RR221, ENGINEERING RESEARCH AND DEVELOPMENT BRANCH, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, 1979.

The report describes the testing of a trapezoidal box girder bridge. The two lane bridge was a simply supported structure 140 ft. long and 34 feet wide. No skew and no superelevation were present. The superstructure consisted of two trapezoidal steel box girders composite with the concrete deck.

The testing of the bridge included measurement of reaction forces and structural steel strains due to construction load, live load and temperature changes and measurement of reinforcing steel strains due to live load-strains in the cross bracings and intermediate diaphragms due to construction, live loads and temperature changes, etc.

An extensive description of instrumentation is included. The testing was carried out using two testing vehicles of 5 axles each. Deflections, strains, and reactions were monitored for 48 load positions for each load level. A concentrated load of 100 kips was applied to the deck at 14 different locations.

The results are presented in a tabular form for reactions. The average variation between analysis and test results was 5% on the conservative side.

Transverse deflections are presented graphically at centerline and quarterspan. The analysis results were consistently higher than test results, but if concrete modulus of elasticity was modified for higher strength concrete the results were almost identical.

The longitudinal strains compared extremely well with the calculated values and are presented graphically.

72. HOLOWKA,M., CSAGOLY,P.F., **"TESTING OF A COMPOSITE PRESTRESSED CONCRETE AASHTO GIRDER BRIDGE"**, RR222, RESEARCH AND DEVELOPMENT DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, 1980.

The report describes the tests performed on the South River Bridge, which is a two lane bridge with 3 spans of 60-70-60 ft., and overall width of 30 ft. 10 inches. The superstructure consisted of four simply supported AASHTO type 3 girders with a composite concrete deck, designed to act continuously for live and superimposed dead loads. Girder spacing was 7 ft. 10 inches and there was a skew angle of 17 degrees.

Two series of live load tests were performed. The first series of tests was testing of the concrete deck slab with a simulated wheel load. The second series of tests was aimed at establishing the behavior of the concrete deck as an integral component of the superstructure.

A concentrated load (100 kips) was applied to the deck at 7 different locations. For the overall testing two testing vehicles of five axles were used. Load locations and combinations are explained in detail.

Load-deflection curves for point loads are given. A graph comparing analytical results from computer analysis and test results is also presented. The results are reasonably close.

For the overall testing, stresses in the reinforcing steel and corresponding concrete stresses are tabulated for each load location.

A grillage analysis was performed, and the deflections obtained were plotted with the test results at various cross-sections (idealizations were made in accordance with section 5 of OHBDC). The results correlated reasonably well.

72A. IMBSEN & ASSOCIATES, INC., **"DISTRIBUTION OF WHEEL LOADS ON HIGHWAY BRIDGES"**, INTERIM REPORT, NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP) PROJECT 12-26, JANUARY 1987..

The effect of live load on the main longitudinal members of bridges is a function of the magnitude and location of truck wheel loads on the bridge deck surface and the response of the bridge to these wheel loads. The determination of the magnitude and location of wheel loads is a complicated problem related to the present and future traffic conditions at the bridge site and the present and future geometry of the roadway carried by the bridge. It includes, in addition to the static effects of wheel loads, the dynamic effects of these wheels that are generally out of phase with other wheels on the same truck and with wheels on adjacent trucks. The entire question of the definition of live load is a complicated one that is beyond the scope of this study. This study focuses on the second factor mentioned above; the response of the bridge to a predefined set of wheel loads.

73. IMBSEN,R.A., SCHAMBER,R.A., **"AN INFLUENCE SURFACE APPROACH TO DETERMINE WHEEL LOAD DISTRIBUTION FACTORS FOR RATING HIGHWAY BRIDGES"**, INTERNATIONAL CONFERENCE ON SHORT AND MEDIUM SPAN BRIDGES, TORONTO, SESSION 7, 1982.

This paper describes a method for determining wheel load distribution factors by using an influence surface approach. Standardized influence surfaces were developed for a family of T-beam bridges. The influence surfaces were developed by normalizing longitudinal and transverse effects so that the entire family of T-beam bridges can be represented by a minimum number of influence surfaces. The method was extended to include the effects of local deterioration. The procedure was presented in a simple format that can be easily incorporated into a bridge evaluation.

74. IMBSEN,R.A., NUTT,R.V., SCHAMBLER,R.A., STEWART,C.F., **"STRENGTH EVALUATION OF EXISTING REINFORCED CONCRETE BRIDGES"**, ENGINEERING COMPUTER CORPORATION, SACRAMENTO, CALIFORNIA, 1982.

This report documents and presents the state-of-the-art on structural strength evaluation of reinforced concrete T-beams, box beams, girder and slab bridges.

75. IRVINE,H.M., **"TORSIONAL ANALYSIS OF BOXGIRDER SUSPENSION BRIDGE"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.100, NO.ST4, APRIL 1974, PP. 789-812.

This paper presents a rational theory for the torsional analysis of the single-span box-girder suspension bridge. It was shown that the torsional elastic theory, which relies on the concepts of strain energy and Castigliano's first theorem, is usually inadequate in predicting the bridge's behavior under torsional live loading, and that recourse should always be made to the torsional deflection theory, developed by Melan.

Three examples were given to show that the torsional analysis is governed primarily by two characteristic dimensionless parameters, i.e., the relative torsional stiffness parameter, and the parameter involving cable geometry and elasticity, and the torsional stiffness of the towers.

76. JANNEY,J.R., HOGNESTAD,E., McHENRY,D., **"ULTIMATE FLEXURAL STRENGTH OF PRESTRESSED AND CONVENTIONALLY REINFORCED CONCRETE BEAMS"**, PCA RESEARCH AND DEVELOPMENT LABORATORIES BULLETIN D7, 1956.

This paper presents the results of a study which was done to provide a direct and quantitative comparison of the flexural behavior and strength of beams with 5 types of straight tension reinforcement:

(1) Pre-tensioned reinforcement.
(2) Post-tensioned grouted reinforcement.
(3) Post-tensioned unbonded reinforcement.
(4) Post-tensioned unbonded reinforcement with deformed bars added.
(5) Conventional deformed bar reinforcement.

The report was based on 19 beam tests; all were 6 by 12 in. cross section and were loaded at the third-points of a 9 ft. span. Particular emphasis was given to ultimate beam strength, deflection recovery at

various percentages of the ultimate load, and load-deflection relationships from zero load to failure. Tests were also done to evaluate the bonding performance of 3/8 in. strand.

76A. JENSEN,V.P., **"ANALYSIS OF SKEW SLABS"**, UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION BULLETIN NO. 332, 1941.

This bulletin studies the analysis of skew slabs with the use of differential equations. The slabs in this study have various skew angles and boundary conditions. The slabs were uniformly loaded or loaded by wheel loads. Also an in-depth study was made on skew slabs with curbs. Various tables are given with the available test data.

77. JENSEN,V.P., ALLEN,J.W., **"STUDIES OF HIGHWAY SKEW SLAB-BRIDGES WITH CURBS PART 1 : RESULTS OF ANALYSES"**, UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION BULLETIN NO. 369, 1947.

This paper presents a continuation of studies being made of highway slab-bridges with curbs, conducted by the University of Illinois Engineering Experiment Station. The designs and analyses were based on a difference equation method which was developed for a range of bridges. Normal span lengths range up to about 30 ft., skew angles up to 60 deg. Only a single standard curb and handrail detail is considered in all designs.

This paper contains numerous tables and curves which show the variation of design moments with the bridge dimensions. These moments are compared with the corresponding moments in similar slab-bridges with curbs, data on which have been obtained in Bulletin 315. General features of the variations of design moments are discussed with a view toward incorporating the results of this bulletin, together with the results of laboratory tests, into a simplified design procedure of skew-slab bridges with curbs.

78. JORGENSON,J.L., LARSON,W., **"FIELD TESTING OF A REINFORCED CONCRETE HIGHWAY BRIDGE TO COLLAPSE"**, TRANSPORTATION RESEARCH RECORD 607, TRANSPORTATION RESEARCH BOARD, WASHINGTON D.C., 1976.

This paper reports on the field testing to failure of a reinforced concrete highway bridge. The slab was 32 ft. wide and 1 ft. thick, and on each edge was cast a 34 by 10 in. curb. Loading was produced by hydraulic rams that were reacted to by overhead steel beams attached to the piers by tension rods through the slabs.

The result of testing and calculations on the reinforced concrete bridge shows:

1. Strength of concrete and steel materials was more than the design minimum values.
2. Measured stresses in the concrete and steel for both the line load and the four-wheel load were very close to the calculated stresses.
3. The load causing first permanent set was accurately predicted by calculating the yield moment in the slab and neglecting the curbs.
4. The collapse load of the bridge was accurately predicted by considering the formation of yield moments along the centerline and over the pier of the bridge.
5. It would take eight HS 20-44 trucks to cause any permanent deflection in the bridge.

79. KENNEDY,J.B., **"WAFFLE SLAB CONCRETE BRIDGES: ULTIMATE BEHAVIOR"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.108, NO.ST6, JUNE 1982, PP. 1285-1301.

This paper presents the results of tests done to determine the structural response of reinforced and prestressed concrete waffle slab bridges under working loads and ultimate collapse loads. Tests are done on five 1/8 scale models of reinforced and prestressed waffle slab bridges.

Results from the experiment are compared to theoretical analysis. The elastic analysis is based on a Fourier series solution, while the ultimate load analysis is formulated using yield-line theory. It was concluded that the test results did verify and substantiate the elastic and ultimate load analyses. The serviceability and load carrying capacity of the reinforced versus prestressed waffle slab bridges are compared. It was found that prestressed waffle slab bridges are much stiffer and stronger.

80. KENNEDY,J.B., EL-SEBAKHY,I.S., **"COLLAPSE LOADS OF CONTINUOUS ORTHOTROPIC BRIDGES"**, JOURNAL OF STRUCTURAL ENGINEERING, VOL.111, NO.8, AUGUST 1985, PP. 1827-1845.

This paper presents the ultimate load analysis of relatively wide continuous orthotropic bridges, both of rectangular and skew planforms. The ultimate load carrying capacity is determined using the yield-line theory. Results from tests carried out on several prestressed concrete waffle slab bridge models are compared to theoretical results. A method by which an

AASHTO HS-20 truck loading can be converted to an equivalent concentrated load is also presented. Comparison of results from the theoretical analysis to those from tests on bridge models verifies the assumed yield-line patterns as well as substantiates the reliability of the yield-line theory to estimate the collapse loads. A design example illustrated the use of the equations derived.

80A. KENNEDY,J.B., GUPTA,D.S.R., **"BENDING OF SKEW ORTHOTROPIC PLATE STRUCTURES"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.102, NO.ST8, AUGUST 1976, PP. 1559-1574.

This report develops a series solution to analyze skew orthotropic plate structures with applied uniform and concentrated loads. Various skew angles and boundary conditions are considered. Also studied in this report are the effects of flexural rigidity ratio, aspect ratio, and torsional rigidity. It was shown that the moment with a uniform load decreases with an increase in the skew angle.

81. KHACHATURIAN,N., ALI,I., THORNE,L.T., **"INVESTIGATION OF PRESTRESSED CONCRETE FOR HIGHWAY BRIDGES, PART II: ANALYTICAL STUDIES AMONG VARIOUS DESIGN CRITERIA FOR PRESTRESSED CONCRETE"**, UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION BULLETIN NO. 463, 1962.

This report presents an analytical study of the design criteria for prestressed concrete beams. The objectives of the study were:

1. To study the criteria for service loads.
2. To study and present simplified methods for calculating the ultimate flexural capacity of beams.
3. To study the relationship between the allowable stresses at service loads and the safety factors against ultimate failure.

The study was limited to simply supported beams but included both composite and non-composite construction.

82. KINNIER,H.L., BARTON,F.W., **"RIGID FRAME HIGHWAY BRIDGE STUDY"**, TRANSPORTATION RESEARCH RECORD 607, TRANSPORTATION RESEARCH BOARD, WASHINGTON D.C., 1976.

This paper reports on the experimental and analytical study of a rigid frame highway bridge. The bridge consists of five, three-span, welded rigid frames. Experimental data included strains and deflections at midspan of the girders and strain data in the vicinity of one of the haunches. A test vehicle loaded to simulate an HS 20-44 loading made 35 test runs. A theoretical analysis of the rigid frame bridge was conducted to verify the experimental data collected and provided additional information in regions where experimental data were lacking. This study shows:

1. Midspan flexural stresses and deflections were sensitive to the transverse position of test vehicle on concrete deck.
2. The estimated values of the ratio of moduli of elasticity of steel to concrete and the effective width of the composite concrete slab have only a small effect on section modulus of bottom fibers.
3. Influence diagram for moment and deflection were not appreciably affected by various models of the haunch in the finite element analysis.
4. Influence diagram for midspan moments and deflections were not appreciably affected by various support condition assumptions at the abutments and slant legs; however, the influence diagram for moment at either side of the haunch were greatly affected by above-mentioned support conditions.

83. KISSANE,R.J., **"FIELD TESTING OF AN ORTHOTROPIC BRIDGE"**, RESEARCH REPORT 35, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, DECEMBER 1975.

Field measurements of static live load strains and deflections of an 88 ft. simple span orthographic-plate-deck bridge are compared with a theoretical analysis that represents the structure as a planar grid.

Test results were presented as longitudinal and transverse stress distributions and deflections.

It was concluded that the planar grid analysis method is a reliable analytical tool for predicting stresses and deflections for service loads in this type of a structure.

84. KISSANE,R.J., **"LATERAL RESTRAINT OF NON-COMPOSITE BEAMS"**, RESEARCH REPORT 123, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, AUGUST 1985.

Full scale laboratory and field testing was performed to determine the restraint to elastic buckling of a steel beam supporting a non-composite concrete deck. In addition to laboratory testing another beam was loaded to flange yield without indication of lateral instability. Loads were applied through a 6 in. thick reinforced concrete slab having no mechanical or chemical bond to the beam.

The field test showed that the induced live-load bending was less than 15% of the design value. Based on the results obtained, it was concluded that lateral buckling of non-composite bridge members is unlikely to occur in service.

85. KISSANE,R.J., BEAL,D.B., **"FIELD TESTING OF HORIZONTALLY CURVED STEEL GIRDER BRIDGES: FOURTH INTERIM REPORT"**, RESEARCH REPORT 27, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, MAY 1975.

Experimentally determined response of a symmetrical, two-span, continuous, horizontally curved steel box girder bridge is compared with a theoretical analysis representing the same structure as a planar grid. The structure evaluated is a three-girder bridge with a centerline span length and radius of 112.7 and 290 ft. respectively. Field measurements consisted of strains, deflections, rotations, and cross-section deformations in one span of the structure.

Test results show that the experimental in-plane bending moments for dead and static live loads were approximately 86% of their respective theoretical values. Comparison with the proportion of total load carried by the individual girders, however, were within 6 percent. The maximum live load distribution factor for this structure is smaller than the value used in design of straight box-girder structures. Increased torsional stiffness resulting from the closely spaced internal diaphragms is believed to have caused this favorable effect.

86. KISSANE,R.J., BEAL,D.B., **"FIELD TESTING OF HORIZONTALLY CURVED STEEL GIRDER BRIDGES: THIRD INTERIM REPORT"**, RESEARCH REPORT 8, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK STATE DOT, ALBANY, NEW YORK, JULY 1972.

The experimentally determined response of a symmetrical, two-span, continuous, horizontally curved steel girder bridge under dead and static live load conditions is compared with a theoretical analysis representing the structure as a planar grid. The structure evaluated is a five-girder bridge with a centerline length and radius of 200.25 and 265.5 ft., respectively. Field measurements consisted of strains, deflections, and rotations in one span of the structure.

Test results showed that the planar grid analysis method, with properly specified member properties, is a reliable analytical tool for predicting deflections and in-plane bending moments. Differences between experimental and theoretical values are noted, and are shown to be insignificant with regard to the design of the structure. However, the experimental results show that the magnitude of lateral flange bending stresses due to dead load, which cannot be determined with the existing theoretical method, are significant.

87. KOSTEM,C.N., **"OVERLOADING OF HIGHWAY BRIDGES - A PARAMETRIC STUDY"**, FRITZ ENGINEERING LABORATORY REPORT NO. 378B.7, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, 1976.

This paper presents the results of a parametric study on the overloading response of right simple span beam-slab bridges with reinforced concrete deck and prestressed concrete I-beams.

Nine bridges with span lengths of 40, 70 and 100 ft. having 5,7, and 8 beams are designed in accordance with current specifications. These bridges are subjected to 5 overload vehicles each, resulting in 45 case studies. Each bridge is loaded by the vehicles on predefined traffic lanes in order to produce the maximum flexural response at the midspan of the bridge.

For various load levels, the damage that the bridge will sustain and the maximum tensile and compressive stresses in the beam and slab are evaluated by use of a finite element program called BOVA (Bridge OVerload Analysis). Examples and recommendations for the implementation of the findings for overload permit issuance operations are included.

The results of a pilot study on the effects of deck deterioration on the load carrying capacity of the bridges are also presented.

88. KOSTEM,C.N., **"OVERLOADING BEHAVIOR OF BEAM-SLAB TYPE HIGHWAY BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 378B.8, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, JULY 1977.

This paper presents the summary of the research program on the prediction of the overload response of simple span beam-slab highway bridges with reinforced concrete deck and prestressed concrete I-beams. The analytical developments and numerical comparisons pertaining to the investigation were not included in this paper, as they have already been presented in previous technical reports. This paper presents only the highlights of the observations made in different phases of the research. Recommendations and conclusions based on the overall research program have been enumerated with appropriate referencing to the detailed description of the relevant problem area.

89. KOSTEM,C.N., **"FURTHER PARAMETRIC STUDIES ON THE OVERLOADING OF HIGHWAY BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 434.2, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, AUGUST 1980.

This paper presents the results of a parametric study on the overloading response of simple span beam-slab bridges with reinforced concrete deck and prestressed concrete I-beams. Six bridges with span lengths of 40' and 70' having 6 and 7 beams were designed in accordance with current specifications. Each bridge was loaded by a vehicle on pre-defined traffic lanes in order to produce maximum flexural response at the midspan of the bridge superstructure.

The study was designed to quantify the effects of:

1. Spacing of bridge beams.
2. Use of inside versus outside lanes.
3. Bridge deck deterioration on the overload response of bridge superstructures.

Program BOVA (Bridge OVerloading Analysis) was used to determine the response of the bridges when subjected to the vehicle loadings. Output from the program was abstracted and presented in tabular form.

90. KOSTEM,C.N., **"OVERLOADING OF PRESTRESSED CONCRETE I-BEAM HIGHWAY BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 434.3, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, JANUARY 1985.

This paper presents a summary of the findings of the research program on the overload response of simple span beam-slab highway bridges with reinforced concrete deck and prestressed concrete I-beams. Specific recommendations were provided for bridge engineers, bridge inspectors, and overload permit officers in order to minimize the adverse effects of overloaded vehicles. Guidelines were provided to identify the load levels which can traverse the bridges without violating the serviceability limits.

This report contains the summary of the findings of two extensive research programs:

1. Overloading behavior of beam-slab type highway bridges.
2. Implementation of program BOVA and a parametric study on overloading.

The detailed description of the case studies and the analytical research were referenced in the report for further in-depth review of the investigations.

91. KRABBE,I., **"THE INTERACTION OF CHORDS AND FLOOR IN TRUSS BRIDGES"**, DER STAHLBAU, NO.8, APRIL 14, 1939.

This paper presents a theory on the participation of floor systems in bridges with the trusses or girders. This distribution of stresses between chords and floor is dependent on:

1. Elongation of each chord member by a force 1.
2. Elongation of the stringers by a force 1, acting at the center of gravity of the connections.
3. Horizontal deflection of the floorbeams under a loading 1.
4. The relative levels of stringers and the chords next to the floor.

The mathematical analysis given agrees with the test results on a through Warren truss single-track railroad bridge of approximately 50 ft. span obtained in Germany.

92. KRYZEVICIUS,S., **"TESTING AND EVALUATION OF THE McINTYRE RIVER BRIDGE WIDENING"**, SRR-84-07, RESEARCH AND DEVELOPMENT BRANCH, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, 1984.

In the report a comparison is made between conventional bridge design analysis and test results of McIntyre River Bridge.

Both the original bridge and the added portion of 30 ft. width are of an identical rigid frame type. The bridge has a 25 degree skew angle (Skew angle for bridges in which the plan form is a parallelogram is the angle obtained by subtracting the acute angle of the parallelogram from 90 degrees). The old and new portions of the bridge are interconnected along the junction of deck by reinforcing steel dowels.

Influence surface charts were used to establish moments and shears at critical deck slab locations (center, obtuse corner etc.).

The methods based on slab theory and assuming full strains have demonstrated good agreement with the test data.

The results were tabulated as strains in different portions of structure for each loading case. A brief description of the instrumentation is also presented.

93. LASH,S.D., NAGARAJA,R., **"ULTIMATE LOAD CAPACITY OF BEAM AND SLAB BRIDGES"**, REPORT NO. RR159, DEPARTMENT OF HIGHWAYS, ONTARIO, MAY 1970.

Failure tests were performed on ten 1/10 scale and two 1/4 scale models of prototype bridges of 60 ft.

span. In some tests the prototypes were designed by conventional (WSD) design methods using AASHTO H20-S16 loading; others were designed for a "research loading" and in conjunction with strength and limit design.

The most interesting part of this paper is its utilization of yield line theory. Although at first, because of failure due to torsion, the proposed failure patterns were not observed, later by increasing the web reinforcement the proposed failure patterns were attained. The study also suggests that the diaphragms in the interior of the bridge are unnecessary. It is also mentioned that the AASHTO and CSA-S6 provisions were insufficient to carry the added torsional shear stress caused by abnormal loads.

Load deflection curves for some of the loadings are presented; also presented are some figures related to unit cost of construction.

94. LIN,C.S., VANHORN,D.A., **"THE EFFECT OF MIDSPAN DIAPHRAGMS ON LOAD DISTRIBUTION IN A PRESTRESSED CONCRETE BOX-BEAM BRIDGE -PHILADELPHIA BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO.315.6, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, JUNE 1968.

This paper presents a study to experimentally investigate the effects of midspan diaphragms on load distribution in highway bridges constructed with prestressed concrete box-girders. The test bridge consisted of five identical precast prestressed hollow box girders, covered with a cast-in-place reinforced concrete deck. The bridge was tested first with the diaphragms in place, and then again after the diaphragms had been removed.

Results showed that the diaphragms did transmit load laterally, but owing to compensating effects when various lanes were loaded, the experimentally determined distribution factors were not appreciably affected. It was also found that for interior girders, the experimental distribution factor was considerably less than the design value, while the experimental values for exterior girders were greater than the design value. The effects of girder spacing and curbs were also studied in this report.

95. LOWE,P.A., FLINT,A.R., **"PREDICTION OF COLLAPSE LOADINGS FOR COMPOSITE HIGHWAY BRIDGES"**, PROCEEDINGS OF INSTITUTION OF CIVIL ENGINEERS, LONDON, VOL.48, 1971, PP. 645-658.

Two one-sixth scale, single span, simply supported, skewed models were tested. No internal diaphragms or stiffeners were provided. Model 1 consisted of two girders with a total width of 1.12 meters, and Model 2 consisted of eight girders with a width of 4.27 meters. A scaled dead load was applied to six points in the web of each girder throughout the curing and testing period. Ultimate load on Model 1 was 2.94 HB. The dead load was removed prior to failure. Model 2's ultimate load was 1.0DL + 3.74HB.

96. LOWE,P.A., **"PREDICTIONS OF LOADINGS CAUSING UNSERVICEABILITY OF REINFORCED CONCRETE AND COMPOSITE HIGHWAY BRIDGE"**, THESIS FOR Ph.D., UNIVERSITY OF LONDON, LONDON, JULY 1969.

This paper describes a theoretical and experimental investigation into the collapse behavior of single span, simply supported, reinforced concrete highway bridges and composite steel girder and deck slab highway bridges.

Failure tests on two slab models and two composite models are described. Due to the cracking strength of the slab sections, the theory underestimates the strength of the slab models. From the results of a double composite girder model with a 30 deg. skew, the application of the no kinking yield criterion to composite girders is confirmed. The dynamic response, the damping behavior, the elastic deflections and strains, the effect of concentrated wheel loads, and the collapse behavior of an eight girder composite bridge model with a scale of one sixth are described.

It has been concluded that a good estimate of the ultimate strength of the slab and composite highway bridges can be obtained from lower and upper bounds to the limit load based on thin plate, small deflection, elastic-plastic theory and yield line theory respectively.

97. MAEDA,Y., MATSUI,S., KURITA,A., KAMEI,M., **"RATING AND EVALUATION OF FIRST-BUILT COMPOSITE GIRDER BRIDGE IN JAPAN"**, REPRINT FROM THE FINAL REPORT, INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERING (IABSE) SYMPOSIUM, WASHINGTON D.C., 1982.

This paper presents a comprehensive study on the rating and deterioration and the evaluation of existing static strength and remaining life of the first-built composite girder bridge in Japan. The bridge consisted of 18 spans of 12 m length of composite I-beams, 7 spans of 12 m length of composite welded girders, and 2 spans of 10 m length of non-composite I-beams.

Based on the measurements of static strengths, fatigue strengths, traffic, and load spectra, and

through the tests of full-size girders or specimens and probability analysis, it was observed :

1. Deterioration, reduction of static strength and cumulative fatigue damage were scarcely observed after 25 years of service.

2. Probability of failure of the bridge was less by 2-orders than the conventional values of 10^{-4} ~ 10^{-6}.

3. The remaining life of the bridge seemed to be 100 years more under the same traffic load spectra and traffic volume as observed in 1980.

4. The soundness of the bridge was dependent on the careful design to choose a small spacing of girders and a thick slab, the use of quality assured materials, and rather smaller traffic loads and less volume.

98. MAEDA,Y., SAEKI,A., ENDO,M., NISHIBORI,T., KURITA,A., REIBA,S., **"BEHAVIOR OF FIRST-BUILT COMPOSITE GIRDER BRIDGE IN JAPAN"**, 11TH CONGRESS VIENNA, REPRINT FROM THE FINAL REPORT, INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERING (IABSE), 1980.

This paper presents the results of testing done on a 25 year old bridge to determine the structural behavior of the bridge. The bridge was the first-built steel-concrete composite girder bridge in Japan and had 18 spans of 12 m length of composite I-beams, 7 spans of 12 m length of composite welded girders, and 2 spans of 10 m length of non-composite I-beams. Testing consisted of material properties tests, flexural strength tests of single and two-web composite girders, and fatigue tests. The results showed no particular reduction in strengths even after 25 years of service. This was attributed to the small spacings of main girders, careful construction resulting in excellent quality of concrete, regular maintenance work, and slow movement of trucks due to traffic crossings at both ends of the bridge.

98A. MASSONNET,C., **"METHODE DE CALCUL DES PONTS A'POURTES MULTIPLES TENANT COMPTE DE LEUR RESISTANCE A'LA TORSION"**, INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERING (IABSE), PUBLICATIONS, VOL.10, 1950, PP.147-182.

This author generalizes Guyon's method, which is based on the assumption of a continuous grid of longitudinal and transverse beams, to include the effect of the torsional resistance of these structural parts. Numerical values are given for the transverse distribution coefficients of the loads for all bracing parameters, and for all values of the torsional stiffness of the beams. Tables are presented which make it possible to calculate the characteristic coefficients of the bending moments in the transverse beams.

The use of the Fourier series allows an accurate determination of the influence of any load system. The method not only furnishes more accurate results than the classical methods for bridges of typical construction, but can also be adopted for bridges with continuous longitudinal beams prestressed transversely, and for slab bridges in reinforced or prestressed concrete.

98B. MATLOCK,H., PANAK,J.J., VORA,M., CHAN,J.H.C., **"FIELD INVESTIGATION OF A SKEWED, POST-STRESSED CONTINUOUS SLAB STRUCTURE"**, INTERIM STUDY REPORT NO. 56-X, CENTER FOR HIGHWAY RESEARCH, UNIVERSITY OF TEXAS AT AUSTIN, MAY 1970.

This report describes the results of field load test measurements and analytical comparisons of a skewed, post-tensioned slab structure. Both analytical and test results indicate that the conventional approach of designing equivalent longitudinal strips for a skewed structure of this type does not reflect the observed behavior in which the transfer of load was associated with longitudinal twisting of the narrow and severely skewed structure. It was found that the sidewalk and parapet railing added significantly to the structural stiffness in the longitudinal direction.

99. MATTOCK,A.H., KAAR,P.H., **"TEST OF HALF-SCALE HIGHWAY BRIDGE CONTINUOUS OVER TWO SPANS"**, REPRINT FROM THE JOURNAL OF THE PCA RESEARCH AND DEVELOPMENT LABORATORIES, VOL.3, NO.3, SEPTEMBER 1961, PP. 30-70.

This paper reports an experimental investigation of the behavior of a half-scale highway bridge continuous over two spans when subject to loads at and above service load level. Examination of the results have shown:

1. The behavior of this type of bridge is essentially elastic when subjected to design service loads and appreciable overloads.

2. The torsional stiffness of the girders has a considerable effect on the lateral distribution of concentrated loads applied on the bridge deck.

3. The transverse distribution of loads at and above service load level can be predicted very closely by use of the Guyon-Massonnet theory, provided the torsional stiffness is taken into account.

This paper also provided additional data on the punching shear strength of reinforced concrete deck slabs.

100. MEADES,B., GREEN,R., **"MODEL STUDIES FOR VOIDED POSTTENSIONED CONCRETE SLAB BRIDGES"**, RR195, RESEARCH AND DEVELOPMENT DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, 1974.

A discussion of design, construction, instrumentation, and loading of scale models of a three span, straight slab bridge, and a two-span, skew slab bridge are presented.

Among questions the study tried to answer was "is elementary beam theory adequate to predict the longitudinal moments due to dead load, live loads, and longitudinal prestressing forces?". The answer was that simple beam theory was able to predict total reaction at a support line. However, this theory did not give the distribution of load to individual end reactions nor the distribution produced by eccentric loads.

Also included in the report was a detailed description of finite element analysis used to analyze the two models. The conclusions were that two dimensional analysis was not adequate to predict stresses close to the point of application and that a three-dimensional analysis was required.

100A. MORICE,P.B., LITTLE,G., **"LOAD DISTRIBUTION IN PRESTRESSED CONCRETE BRIDGE SYSTEMS"**, STRUCTURAL ENGINEER, VOL.32, MARCH 1954, PP.83-111.

This paper describes methods which treat the problem through an elastically equivalent uniform system, and the methods of practical calculation using distribution coefficients are explained. For the use of practical design purposes, the results of computational work of Guyon and Massonnet for non-torsion and torsion structures are given in the form of graphs. A method of calculation and the effects of torsion are discussed.

Theoretical results are compared to test results of a number of interconnected prestressed beam systems, and the agreement is good. The effects of distribution are virtually eliminated by a simple support, and do not appear in the unloaded span of a continuous specimen. The main conclusions from the tests were that the simply-supported grillages behaved as non-torsion grillages, and that the deflections and the bending moments were forecast with agreeable accuracy by the method of distribution coefficients initiated by Guyon. The continuous grillage showed good agreement with torsion calculations based upon the analysis of Massonnet.

101. MOTARJEMI,D., VANHORN,D.A., **"THEORETICAL ANALYSIS OF LOAD DISTRIBUTION IN PRESTRESSED CONCRETE BOX-BEAM BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 315.9, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, OCTOBER 1969.

This paper presents a theoretical study of the vehicular load distribution in spread box-beam bridges. The box-beam bridges were composed of a number of precast prestressed concrete box beams, equally spaced and spread apart, and a cast-in-place composite slab. A method of analysis was developed for beam-slab bridges, particularly to spread box-beam bridges, by reducing the bridge to an articulated structure by introducing a series of beam and plate elements. The method of solution employed was a flexibility type.

The validity of the theoretical analysis was verified by comparison with the results of field tests on four different spread box-beam bridges. Based upon the results obtained, design procedures for the determination of lateral live-load distribution were developed and recommended.

102. McCLURE,R.M., WEST,H.H., ABDEL-HALIM,M., **"OVERLOAD TESTING OF AN EXPERIMENTAL SEGMENTAL BRIDGE"**, FHWA/PA 82-011, RESEARCH PROJECT 75-3, THE PENNSYLVANIA TRANSPORTATION INSTITUTE, JULY 1982.

This paper presents the results of tests done on an experimental precast-prestressed segmental bridge which was designed by the Pennsylvania D.O.T. The objectives of the investigation were:

1. To make field measurements on a full-scale bridge.
2. To study overload behavior.
3. To make a crack survey of the bridge before and after testing.
4. To develop an analytical procedure capable of predicting the complete post-elastic response of the bridge.

Girder B of the experimental segmental bridge was tested to failure in increments of the design load by using four points of loading located over the webs to give a longitudinal bending-type failure. An analysis procedure based on the finite element method was developed to predict the complete loading deformation response of girder B. The girder was also analyzed by the standard theoretical analysis of prestressed concrete structures. Theoretical results obtained by

these two methods were compared with the experimental results. This paper provides exceptional detail in the form of diagrams and explanations on every aspect of the experiment.

103. NARUOKA,M., **"MEASUREMENT OF THE STRESS AND DEFLECTION OF KANZAKI BRIDGE"**, INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERING (IABSE) PUBLICATIONS, VOL. 14, 1954.

In order to establish the difference between a single beam structure and parallel beam structure, a static load test was done on Kanzaki Bridge, which is the first composite bridge built in Japan. The span was about 35 ft., and there were 5 girders.

The report is rather brief and does not provide much information about the tests. Results are summarized in two tables, one giving the stress ratios on each girder due to different loadings and the other giving the deflection ratios.

104. NELSON, BEVERIDGE, ARTHUR, **"TESTS ON MODEL COMPOSITE BRIDGE"**, INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERING (IABSE) PUBLICATIONS, VOL. 23, 1963.

This paper reports on a series of tests performed on a 1:4 scale model of one span of a composite steel box girder bridge. The girder consisted of a steel box stiffened orthogonally on the inside, with a concrete deck slab connected to it by stud welded shear connectors.

The prototype has 42 spans, 31 of which are 180 ft. long and this span was chosen as the basis for model tests. Final failure took place by shearing of all the studs between the load point and the nearer support. The total force transmitted through the studs at failure was 110t (110,000 kg) giving a shear stress on the studs of 18.2t/sq in. The shear strength of the studs when tested independently was 20t/sq in.

Failure load of 117t is equivalent on the prototype to the shear due to full dead load plus 4.96 times H.A. load and to bending moment due to full dead load plus 4.37 times H.A. load.

Analysis of the tests led to the following important points:

(1) The incomplete interaction between the concrete slab and the steel box. During the elastic stage, the share of load carried by the concrete was approximately 90% of that calculated for full interaction.

(2) The reduction of the torsional stiffness due to the concentrated load. Concentrated loads applied eccentrically over one of the webs produced sway distortion equivalent to a reduction of 70% in the torsional rigidity.

(3) Buckling strength of the web-stiffener assembly overrides buckling of individual web-plate panels.

105. NEWMARK,N.M., **"DESIGN OF SLAB AND STRINGER HIGHWAY BRIDGES"**, PUBLIC ROADS, MARCH 1943, PP. 157-164.

This paper is one of the earliest papers done in designing the slab and stringer bridge. Three types of such bridges considered in this paper are:

1. The I-beam bridge, which consists of a concrete deck continuous over steel beams, with the beams in the direction of the traffic.

2. The composite I-beam bridge, which has shear connectors between the beams and slab which make the structure act as a composite beam.

3. The concrete T-beam bridge, with concrete beams running in the direction of traffic.

This paper includes an illustrative design of the composite I-beam bridge which includes the slab, the beams and the shear connectors.

106. NEWMARK,N.M., SIESS,C.P., PECKHAM,W.M., **"STUDIES OF SLAB AND BEAM HIGHWAY BRIDGES"**, UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION BULLETIN NO. 375, JANUARY 1948.

This paper reports on laboratory tests done on five I-beam bridges having angles of skew of 30 and 60 deg. The structures tested were quarter-scale models of simple span bridges. The results of strain measurements at various points on skew bridges are compared with the corresponding data for right bridges.

The results of the tests indicate two principal effects of skew on the behavior of I-beam bridges:

1. The maximum moments in the beams are decreased slightly, but only for larger angles of skew.

2. The controlling moments in the slab - the positive moments at the center of a panel - are increased.

107. NOWAK,A.S., AGARWAL,A.C., **"CALIBRATION OF ONTARIO HIGHWAY BRIDGE DESIGN CODE"**, SRR-81-01, POLICY PLANNING AND RESEARCH DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, 1981.

The report describes the procedure and results of the calibration of the Ontario Highway Bridge Design Code. It covers calculation of load factors,

performance factors for composite steel girders, pretensioned concrete girders, and post-tensioned concrete decks.

Nineteen recently built bridges were selected, and proportions of load components calculated from these bridges were assumed to be typical for future structures.

108. ORGANIZATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD) ROAD RESEARCH GROUP, **"EVALUATION OF LOAD CARRYING CAPACITY OF BRIDGES"**, ROAD RESEARCH, PARIS, DECEMBER 1979.

This report presents a state-of-the-art review on the evaluation of load carrying capacity of existing road bridges. It reviews vehicle and traffic characteristics with the aim of examining actual bridge loading patterns, and it discussed the growing problem of exceptionally heavy vehicles.

108A. OSHIRO,T., HAMADA,S., **"STRUCTURAL PERFORMANCE AND BENDING TEST OF DETERIORATED REINFORCED CONCRETE BRIDGES"**, STRENGTH EVALUATION OF EXISTING CONCRETE BRIDGES, AMERICAN CONCRETE INSTITUTE PUBLICATION SP-88, 1985.

The primary objective of this study is to investigate the structural performance of two deteriorated reinforced concrete bridges and isolated test beams cut out of the same bridges at the time of replacement. Field and bending tests were conducted from which the strength of existing bridges and isolated beams was observed. Correlations of the values of the strength obtained from these two tests give important data to be used for evaluation of existing deteriorated bridges.

108B. OZBEK,A.M., **"LATERAL LOAD DISTRIBUTION IN BEAM AND SLAB HIGHWAY BRIDGES"**, M.Sc. THESIS, UNIVERSITY OF TENNESSEE, KNOXVILLE, JUNE 1987.

This paper is concerned with the problem of transverse load distribution in beam and slab highway bridges. Six beam and slab highway bridges that were tested to failure are analyzed to estimate their yield moment capacity utilizing different load distribution methods.

108C. PAGE,J., **"LOAD TESTS TO COLLAPSE ON TWO ARCH BRIDGES AT PRESTON, SHROPSHIRE AND PRESTWOOD, STAFFORDSHIRE"**, RESEARCH REPORT 110, TRANSPORT AND ROAD RESEARCH LABORATORY, CROWTHORNE, BERKSHIRE, 1987.

This report describes the tests to failure of two arch bridges. Preston Bridge was built with an elliptical sandstone arch 14.2" (360 mm) thick and brick spandrel walls and parapets. Prestwood Bridge had a brick segmental arch 8.7" (220 mm) thick and was in poor condition, with parapets removed and a distorted arch. A line load was applied on the full width of the bridge at 1/3 span and 1/4 span respectively. Preston Bridge collapsed due to crushing of the arch ring beneath the load line at a maximum load of 474 kips (2110 kN). Prestwood Bridge collapsed as a 'four hinged mechanism' after a maximum load of 51 kips (228 kN). Test results are compared with theoretical analyses and a model test.

109. PATEL,N.J., **"TESTING AND EVALUATION OF IRVINE CREEK BRIDGE"**, SRR-84-11, RESEARCH AND DEVELOPMENT BRANCH, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, NOVEMBER 1984.

The report describes the structural evaluation and live load test studies performed on Flack River Bridge. The bridge consisted of Pony trusses spanning 65 feet with concrete deck cast over stringers and floor beams.

The analytical solution was done in accordance with the Ontario Highway Bridge Design Code (OHBDC) Section 14 simplified method.

Calculated floor beam moments were much higher than measured values but were reasonably close when correction was made for load sharing (using Bakht and Jaeger's methodology. An estimated live load distribution factor of 0.6 was used). Deflections also compared within 10% of test results.

110. PAULET,E.G., **"FACTORED LOADS IN AASHTO SPECIFICATIONS"**, SPECIAL PRESENTATION TO FHWA AND U.S. DOT.

This paper presents the development of modern highway bridge specifications, specifically the evolution of the overload provision in the AASHTO specifications from 1931 to 1973. A discussion of the use of load factors is also included in this paper.

111. PETERSON,W.S., KOSTEM,C.N., **"THE INELASTIC ANALYSIS OF BEAM-SLAB HIGHWAY BRIDGE SUPERSTRUCTURES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 378B.5, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, MARCH 1975.

This paper describes an analysis scheme to predict the overload response of simple span beam-slab type highway bridges with reinforced concrete deck slab and reinforced or prestressed concrete I or rectangular beams. The interaction of beam and slab components and material non-linearities are considered. It is assumed that the inelastic response of the superstructure is governed by the flexural behavior, i.e., excluding the effects of transverse and torsional shear.

The developed scheme utilizes the finite element displacement method, discretizing the superstructure into layered beam and plate bending elements. The accuracy of the method is illustrated by comparisons between five full-scale bridge tests and analytical results. Satisfactory agreement was obtained for all test cases. The analytical model and solution technique were verified.

111A. PHILLIPS,M.H., **"DESTRUCTIVE TESTING OF BARKERS BRIDGE"**, CENTRAL LABORATORIES REPORT 5-85/1, CENTRAL LABORATORIES, LOWER HUTT, NEW ZEALAND, MAY 1985.

Barkers Bridge is the third concrete bridge to be tested to destruction by Central Laboratories. The first two bridges were single span cast-in-situ T-beam bridges with the four main beams built into the abutments. A large portion of the overstrength of these bridges was attributed to the end fixity of the main beams. Barkers Bridge was chosen for testing as it was similar in construction to the other two bridges, but the center span was effectively simply supported.

Initially, a vehicle of known weight was used to measure the elastic response of the bridge. This was followed by loading with hydraulic jacks two main beams and then the deck slab to destruction.The vehicle load testing demonstrated that the handrail system, although usually ignored in design, carries a significant amount of load at the level of stress generated by normal live loads.

The ultimate capacity of the bridge was reached with the crushing of the curb. Curbs are often ignored for rating calculations of concrete bridges. Calculations show that the curb upstands increase the ultimate capacity of this bridge by 25%. The deck slab was loaded to 10 times the HN wheel load before the slab failed by punching shear. Wheel loads on bridge decks in existing classification and rating procedures are limited by the flexural strength of the deck.

112. PUCKETT,J.A., REASCH,L.R., WILSON,C.H., **"MICROCOMPUTER VERSION OF BRIDGE RATING AND ANALYSIS OF STRUCTURAL SYSTEMS (BRASS-PC)"**, PROCEEDINGS OF SECOND ANNUAL INTERNATIONAL BRIDGE CONFERENCE, PITTSBURGH, PENNSYLVANIA, JUNE 1985, PP.97-100.

This paper outlines the features and capabilities of BRASS-PC, a microcomputer-based finite element code written for the IBM-PC XT and fully compatible computers. The program is dedicated to the analysis of continuous and simple span bridges subjected to moving concentrated and uniform loads. The computer code has three main components:

1. Interactive input and processing.
2. Structural analysis.
3. Rating and postprocessing.

This microcomputer program BRASS-PC will provide the bridge design community with a valuable tool for the analysis, rating, and design of single and multispan bridge structures.

113. REDDY,V.M., **"ULTIMATE LOAD BEHAVIOR OF COMPOSITE STEEL-CONCRETE BRIDGE DECK STRUCTURES"**, THESIS FOR PHD, UNIVERSITY OF EDINBURGH, ENGLAND, APRIL 1968.

This paper deals with the ultimate load behavior of simply supported composite steel-concrete deck structures subjected to concentrated loads. Simplified yield-line theory is applied to upper-bound solutions for the ultimate load. The theoretical values are compared with the results of experiments carried out on model bridges.

114. ROWE,R.E., **"ABNORMAL LOADING ON TWO TYPES OF SHORT SPAN BRIDGE"**, INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERING (IABSE) PUBLICATIONS, VOL.20, 1960.

Three composite slab and girder bridge models were tested to determine the deterioration in the distribution properties and the applicability of ultimate load methods for design of transverse reinforcement.

All of the three models tested were about 1/3 scale models of an actual highway bridge. The report takes each test separately and gives detailed information on the materials used, the construction, and the tests carried out. The lateral load distribution characteristics of different models are

emphasized and lateral deflection plots for theoretical distribution factors and test results are shown.

115. RUIZ,W.M., **"EFFECTS OF OVERLOADS ON SHORT SPAN BRIDGES"**, INTERNATIONAL CONFERENCE ON SHORT AND MEDIUM SPAN BRIDGES, SESSION 7, TORONTO, 1982.

This paper evaluates the overload capacity of typical short span bridges (S<100 ft.) based on AASHTO operating rating criteria, in terms of its HS20-44 loading. The overloading effect is evaluated in terms of the fatigue life of the structures taking into consideration the frequency of load application and typical material properties under repeated loading of the structural members.

Results have shown that:

1. Effects of live load overloading for short span bridges tend to decrease as span increases. This is a direct result of reduction in LL/DL ratio as span increases.

2. Under the level of overloading considered, structures with spans ranging up to 50 ft. are being seriously overloaded with a resulting rapid deterioration and possible collapse of structure.

3. In general, short-span bridges designed for HS 20-44 loading can sustain 1.1 of design load for an indefinite period of time.

4. Steel composite bridges up to spans of 100 ft. are being overloaded in terms of their operating rating criteria. Those designed without cover plates are not affected, in terms of their fatigue life, but the ones designed with cover plates are seriously affected.

5. For prestressed concrete bridges with a span in excess of 50 ft., present overloading does not exceed AASHTO operating rating criteria.

6. The overload capacity of bridges increases with span length.

116. SABNIS,G.M., **"INNOVATIVE METHODS OF UPGRADING STRUCTURALLY AND GEOMETRICALLY DEFICIENT THROUGH TRUSS BRIDGES, FINAL REPORT"**, REPORT NO. FHWA/RD-82/041, FEDERAL HIGHWAY ADMINISTRATION, BALTIMORE, MARYLAND, APRIL 1983.

This paper presents a study which consisted of:

1. Investigation of current practices in several states to upgrade truss bridges.

2. Literature search for state-of-the-art perspective.

3. Evaluation of information from the FHWA bridge inventory.

4. Search for examples of truss bridge rehabilitation.

The information is used to develop and evaluate various methods to rehabilitate through truss bridges.

Various methods of rehabilitation are formulated, analyzed, and designed to suit the most general condition of truss bridges. This report also discusses several problems which exist with through truss bridges.

The methods are applied to the one existing, typical bridge to demonstrate proposed methods and to identify problems, limitations, and construction procedure as applied to actual bridges. Both specifications and drawings are included, and cost comparisons between rehabilitation and replacement are also presented.

117. SALMÓNS,J.R., MOKHTARI,S., **"STRUCTURAL PERFORMANCE OF THE COMPOSITE U-BEAM BRIDGE SUPERSTRUCTURE"**, JOURNAL OF THE PCI, VOL.16, NO.4, 1971, PP. 21-33.

This paper reports on test results of a proposed composite U-beam bridge superstructure. Three full scale and eight one-half scale pretensioned U-beams were fabricated for this study. Both working stress and ultimate strength behavior of single units and a multi-unit bridge deck were studied, the latter by means of one-half scale models. It was observed that :

1. The overall structural response of the specimens was in close agreement with design calculations. The proposed system can be designed by conventional composite prestressed design procedures and in accordance with AASHO specifications.

2. Behavior of this type of bridge is essentially elastic when subjected to point loads, service wheel loads, and even appreciable overloads.

3. The transverse distribution of load and moments can be studied by deflection distribution as predicted by the Guyon-Massonnet theory.

4. Under the most severe condition of loading the exterior unit carries only 46% of a single load, while a comparable unit in a composite I-girder bridge carries 67%.

5. The wheel load distribution of this type of bridge is comparable to that of a voided continuous slab.

118. SANDERS,JR.,W.W., ELLEBY,H.A., **"DISTRIBUTION OF WHEEL LOADS ON HIGHWAY BRIDGES"**, NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT NO. 83, 1970.

This paper presents a summarized research report to study the distribution of wheel loads in highway bridges and to recommend, where warranted, changes in the "AASHTO standard specifications for highway bridges". The study was limited to short and medium span bridges of the following types: beam and slab, multi-beam, and concrete box girder. The study concluded that the distribution of wheel loads in these bridge types could be accurately determined using the following theories.

1. Beam and slab bridges : Orthotropic plate theory.
2. Multi-beam bridges : Articulated plate theory.
3. Concrete box girder bridges : Prismatic folded plate theory.

Correlations between experimental and theoretical results indicated that the theories do adequately predict the load distribution in the particular bridge types. It was felt that with these new criteria, prediction of wheel load distribution will be more accurate and will be more truly indicative of the behavior of the bridge types studied.

119. SANDERS,W.W., KLAIBER,F.W., ELLEBY,H.A., TIMM,L.W., **"ULTIMATE LOAD TEST OF TRUSS BRIDGE FLOOR SYSTEM"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.102, NO.ST7, JULY 1976, PP. 1383-1398.

This was a modified Parker Type High Truss with decking and wood stringers. Truss spacing was 17'-3". The materials were assumed elastic up to yield strain, and no strain hardening was taken into account. Deviations from theoretical values were attributed to frozen condition of pins. The experimental member forces for vertical members were quite erratic, and lower chord tension member forces differed considerably in magnitude from theoretical values.

120. SANDERS,W.W.,JR., ELLEBY,H.A., KLAIBER,E.W., REEVES,M.D., **"ULTIMATE LOAD BEHAVIOR OF FULL-SCALE HIGHWAY TRUSS BRIDGES: PHASE II SERVICE LOAD AND SUPPLEMENTARY TESTS"**, ENGINEERING RESEARCH INSTITUTE PROJECT 1118S, IOWA STATE UNIVERSITY, AMES, IOWA, 1975.

This paper presents the results of the second phase of a research program designed to study the ultimate load behavior of full-scale highway truss bridges. Two old high-truss single-lane bridges were selected for a test program consisting of service load tests on the two bridges (Hubby bridge and Chestnut Ford bridge) as well as the supplementary tests, both static and fatigue, of eyebar members removed from the two bridges. The field test results of the service loading are compared with the theoretical results of the truss analysis.

121. SANDERS,W.W.,JR., KLAIBER,F.W., ELLEBY,H.A., TIMM,L.W., **"ULTIMATE LOAD BEHAVIOR OF FULL-SCALE HIGHWAY TRUSS BRIDGES: PHASE I ULTIMATE LOAD TESTS OF THE HUBBY BRIDGE - BOONE COUNTY"**, ENGINEERING RESEARCH INSTITUTE PROJECT 1118S, IOWA STATE UNIVERSITY, AMES, IOWA, 1975.

This report details the research and findings of the ultimate load behavior of a high truss bridge. The bridge was composed of four modified Parker type high-truss simple spans, each 165 ft. long.

The objectives of the tests were to:

1. Relate appropriate AASHTO criteria to actual bridge behavior.
2. Determine behavior and capacity of timber bridge decks used in the bridge.
3. Indicate the accuracy of load rating estimation techniques.

Some of the conclusions obtained from the test:

1. The behavior of the timber deck was linear up to about 1/2 of the ultimate load for each deck test.
2. The theoretical capacity of the deck and each floorbeam was approximately equal to the experimentally determined capacity of the deck and floorbeams.
3. The ratings of the bridge and its components averaged about 25% of capacity. The ratings were fairly consistent except for the floorbeams, where the assumption on lateral support conditions for the compression flange caused considerable variation.

122. SARTWELL,D.A., HEINS,JR.,C.P., LOONEY,C.T.G., **"ANALYTICAL AND EXPERIMENTAL BEHAVIOR OF A SIMPLE-SPAN GIRDER BRIDGE"**, HIGHWAY RESEARCH RECORD NO. 295, HIGHWAY RESEARCH BOARD, WASHINGTON D.C., 1976.

This paper presents an analytical technique, finite differences, to predict the actual strains and deflections in a simple girder-slab bridge. These particular items were observed from the experimental-analytical comparison:

1. The parapet and curb were structurally active when loads were applied adjacent to the curb.

2. The bridge system can be equated to an equivalent orthotropic plate.

3. The finite difference technique can be applied in predicting the behavior of a simple girder-slab bridge.

122A. SCANLON,A., MIKHAILOVSKY,L., **"FULL-SCALE LOAD TEST OF THREE-SPAN CONCRETE HIGHWAY BRIDGE"**, CANADIAN JOURNAL OF CIVIL ENGINEERING, VOL.14, NO.1, FEBRUARY 1987.

A full-scale load test to failure of a three-span continuous reinforced concrete highway bridge located in southern Alberta in Canada is described. Load was applied to the structure in two phases. First, precast concrete sections were placed at the center of the mid-span until a load of approximately 427 kips was reached. At this load level a mid-span deflection of 1.1 in. was measured for the interior span. Additional load was applied by jacking the ends of the bridge at the abutment supports. Loading continued until a maximum deflection of 6.2 in. was reached at mid-span. Significant cracking as well as crushing of the compression flange at mid-span were evident. On removal of load, a residual deflection of 4.6 in. was observed indicating that the bridge had been loaded well into the post-yield range without collapsing.

Results of the test are presented in the form of plots of load versus deflection, reactions versus deflection, mid-span moment versus deflection, and deflection profiles at various loading stages. The calculated flexural capacity is compared with measured values.

123. SCHAFFER,T., VANHORN,D.A., **"STRUCTURAL RESPONSE OF A 45 DEG. SKEW PRESTRESSED CONCRETE BOX GIRDER HIGHWAY BRIDGE SUBJECTED TO VEHICULAR LOADING - BROOKVILLE BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 315.5, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, OCTOBER 1967.

This paper presents the results of tests done to evaluate the structural behavior of a prestressed concrete box girder highway bridge of 45 deg. skew, and to compare its behavior to that of a right bridge of similar characteristics.

Moment coefficients were determined by a computer program designed to perform calculations for any girder cross section. Compared to that of a right bridge, moment coefficient values for the skew bridge were generally lower and it was concluded that the effect of skew is to more uniformly distribute the wheel loads over the span length. The magnitudes and distributions of strains in the skew bridge were quite comparable to those of the right bridge, and in general, the magnitudes were slightly smaller. This fact was also attributed to the more uniform longitudinal distribution of load in the skew bridge, and differences in the effective modulus of elasticity.

124. SCHELLING,D.R., **"EFFECTS OF MARYLAND LEGAL VEHICLE WEIGHT LIMITS ON HIGHWAYS AND BRIDGES"**, FINAL REPORT AW081-255-046, DEPARTMENT OF CIVIL ENGINEERING, UNIVERSITY OF MARYLAND, 1982.

This paper presents the results of an investigation to determine the effects of the truck weight limits on the highway pavement, the damage on bridge structures, the cost allocation of trucks for highway pavements, and the cost allocation of various trucks for bridge structures.

The effects of the truck configuration on the bridge structures were determined by a rational structural analysis of those bridge types which are most prevalent and most susceptible to high axle loadings. The results of the analysis indicated that of the 4,533 bridge spans on the Maryland state system that were analyzed, 64% are susceptible (due to their low span lengths and original design loadings) to the current legal axle loadings. Various alternatives and recommendations were presented in this paper to reduce the number of bridge spans being excessively overstressed.

125. SCORDELIS,A.C., BOUWKAMP,J.G., WASTI,T.S., SEIBLE,F., **"ULTIMATE STRENGTH OF SKEW REINFORCED CONCRETE BOX GIRDER BRIDGE"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.108, NO.ST1, JANUARY 1982, PP. 105-121.

This report was based on a study of a large scale 45 degree skew, two-span, composite four cell reinforced concrete box girder bridge model. The model, which was a 1:2.82 scale replica of a typical California Highway System prototype, had overall dimensions of 72 feet in length by 12 feet wide, with two spans and a skew center bent diaphragm.

Load deflection curves are given, showing an ultimate load of 242.6 kips and a first yield of approximately 180 kips. It was concluded that the skew of the bridge increased the overload capacity substantially. The test was performed at the University of California, Berkeley.

126. SCORDELIS,A.C., LARSEN,P.K., ELFGREN,L.G., **"ULTIMATE STRENGTH OF CURVED RC BOX GIRDER BRIDGE"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.103, NO.ST8, AUGUST 1977, PP. 1525-1542.

This paper presents the results obtained in a study of a large-scale curved two-span four-cell reinforced concrete box girder bridge model. The model was a 1:2.82 scale replica of a prototype and the model had a radius of curvature of 100 ft. Experimental and theoretical results were considered for reactions, steel and concrete strains, deflection, and moments due to conditioning overloads producing stress values as high as 2.5 times the nominal design stress. The live-load overload capacity was evaluated and compared with the similar behavior of an earlier tested straight bridge model. The results showed that the bottom slab is a critical part of the box girder bridge and that the girder webs ought to be carefully designed. This is especially true for the bottom corners of exterior girder webs, where high shear stresses from vertical shear forces and torsional moments may act together.

127. SCORDELIS,A.C., BOUWKAMP,J.G., LARSEN,P.K., **"STRUCTURAL BEHAVIOR OF A CURVED TWO SPAN REINFORCED CONCRETE BOX GIRDER BRIDGE MODEL (VOL.1)"**, UC SESM 74-5, STRUCTURES AND MATERIALS RESEARCH, UNIVERSITY OF CALIFORNIA, BERKELEY, 1974.

This is the first of a three volume sequence. In the present volume a detailed study of the instrumentation, construction, and testing of a large scale, horizontally curved, two-span, four cell, reinforced concrete box girder bridge model is presented.

The selection of the model scale, the choice and the location of the instrumentation, and the system of data acquisition are discussed. The reinforcement and the dimensions of the model are given. A complete description of the experimental program is presented. A loading schedule incorporating the various types of loading, support conditions and stress levels is described. Results of control tests on steel and concrete are given.

128. SCORDELIS,A.C., BOUWKAMP,J.G., LARSEN,P.K., **"STRUCTURAL BEHAVIOR OF A CURVED TWO SPAN REINFORCED CONCRETE BOX GIRDER BRIDGE MODEL (VOL.2)"**, UC-SESM-74-6, STRUCTURES AND MATERIALS RESEARCH, UNIVERSITY OF CALIFORNIA, BERKELEY, 1974.

This is the second of a three volume sequence. In the present volume a detailed presentation of the reduction, analysis, and interpretation of the experimental and theoretical results obtained in testing a large scale, horizontally curved, two-span, four cell, reinforced concrete box girder bridge model.

129. SCORDELIS,A.C., BOUWKAMP,J.G., LARSEN,P.K., **"STRUCTURAL BEHAVIOR OF A CURVED TWO SPAN REINFORCED CONCRETE BOX GIRDER BRIDGE MODEL (VOL.3)"**, UC SESM 74-7, STRUCTURES AND MATERIALS RESEARCH, UNIVERSITY OF CALIFORNIA, BERKELEY, 1974.

This is the final of a three volume sequence. In the present volume, detailed experimental and analytical results obtained in testing a large scale, horizontally curved, two span, four cell, reinforced concrete box girder bridge model are presented.

130. SCORDELIS,A.C., BOUWKAMP,J.G., WASTI,S.T., **"STRUCTURAL BEHAVIOR OF A TWO SPAN REINFORCED CONCRETE BOX GIRDER BRIDGE MODEL (VOL.1)"**, UC SESM 71-5, STRUCTURES AND MATERIALS RESEARCH, UNIVERSITY OF CALIFORNIA, BERKELEY, 1971.

A detailed study of the instrumentation, construction, and testing of a large scale, two-span, four cell, reinforced concrete box girder model is presented. The selection of the model scale, the choice and location of instrumentation, and the system of data acquisition are discussed.

A loading schedule incorporating the various types of loading, support conditions, and stress levels is described. Results of control tests on steel and concrete are given. The two main theories analyzing box girder bridge behavior, i.e. the folded plate and finite element methods, are briefly described with reference to the bridge model of the present study. Presentation and interpretation of the test data from the experimental program are not treated in this volume, but are presented in the next volume.

131. SCORDELIS,A.C., BOUWKAMP,J.G., WASTI,S.T., **"STRUCTURAL BEHAVIOR OF A TWO SPAN REINFORCED CONCRETE BOX GIRDER BRIDGE MODEL (VOL.2)"**, UC SESM 71-16, STRUCTURES AND MATERIALS RESEARCH, UNIVERSITY OF CALIFORNIA, BERKELEY, 1971.

A detailed presentation of the reduction, analysis, and interpretation of the experimental and theoretical results obtained in testing a large scale, two-span, four cell, reinforced concrete box girder bridge model is given.

The various computer programs used in obtaining theoretical results are described and compared. The methods and computer programs used for reduction of experimental data are also presented. Results in terms of reactions, deflections, strains and moments for the response of the bridge under dead load, working stress loads, and at overload stress levels are given, and comparisons between experimental and theoretical values are made. A review of the behavior under sustained load during the load history of the model is given with respect to strains, deflections and cracking. The loading to failure and observations of structural behavior during this final phase are considered in detail.

132. SCORDELIS,A.C., BOUWKAMP,J.G., WASTI,S.T., **"STRUCTURAL BEHAVIOR OF A TWO SPAN REINFORCED CONCRETE BOX GIRDER BRIDGE MODEL (VOL.3)"**, UC SESM 71-17, STRUCTURES AND MATERIALS RESEARCH, UNIVERSITY OF CALIFORNIA, BERKELEY, 1971.

Detailed tables of experimental and analytical results obtained in testing a large scale, two-span, four cell, reinforced concrete box girder model bridge are presented. Results in terms of reactions, deflections, strains, and moments are given. The responses of the bridge to point loads, conditioning loads, and truck loadings, all at working stress levels, are tabulated. In addition, tabulated results are given for conditioning loads at overstress levels and for point loads after conditioning overloads. Finally, tables of results are presented for the final loading to failure.

133. SCORDELIS,A.C., BOUWKAMP,J.G., WASTI,S.T., ANICIC,D., **"STRUCTURAL BEHAVIOR OF A SKEW TWO SPAN REINFORCED CONCRETE BOX GIRDER BRIDGE MODEL (VOL.1)"**, UC SESM 80-1, STRUCTURES AND MATERIALS RESEARCH, UNIVERSITY OF CALIFORNIA, BERKELEY, 1980.

This is the first of a four volume sequence as follows: Vol I - Design, Construction, Instrumentation and Loading; Vol. II - Reduction, Analysis and Interpretation of Results; Vol III - Response During Ultimate Loading to Failure; Vol. IV - Detailed Tables of Experimental and Analytical Results.

In the present volume a detailed study of the instrumentation, construction, and testing of a large scale, two-span, four cell, reinforced concrete box girder bridge model is presented. The selection of the model scale, the choice and location of instrumentation, and the system of data acquisition are discussed. The reinforcement and the dimensions of the model are given. A complete description of the experimental program is presented. A loading schedule incorporating the various types of loading, support conditions, and stress levels is described. Results of control tests on steel and concrete are also given.

134. SCORDELIS,A.C., BOUWKAMP,J.G., WASTI,S.T., ANICIC,D., **"STRUCTURAL BEHAVIOR OF A SKEW TWO SPAN REINFORCED CONCRETE BOX GIRDER BRIDGE MODEL (VOL.2)"**, UC SESM 80-2, STRUCTURES AND MATERIALS RESEARCH, UNIVERSITY OF CALIFORNIA, BERKELEY, 1980.

This is the second of a four volume sequence on the structural behavior of a skew, two-span, four cell, box girder bridge model.

In the present volume, a detailed presentation of the reduction, analysis, and interpretation of the experimental and theoretical results obtained in testing a large scale 45 degree skew, two-span, four cell, reinforced concrete box girder bridge model is given.

The various computer programs used in obtaining theoretical results are described and compared. The methods and computer programs used for reduction of experimental data are also presented.

Results, in terms of reactions, deflections, strains, and moments, for the response of the bridge to dead load, working stress loads, and at overload stress levels are given, and comparisons between experimental and theoretical values are made. A review of the behavior under sustained dead load during the load history of the model is given with respect to strains, deflections, and cracking. A comparison is made at all stages between the behavior of the skew bridge studied in this investigation and of similar straight and curved bridges studied previously.

135. SCORDELIS,A.C., BOUWKAMP,J.G., WASTI,S.T., ANICIC,D., **"STRUCTURAL BEHAVIOR OF A SKEW TWO SPAN REINFORCED CONCRETE BOX GIRDER BRIDGE MODEL (VOL.3)"**, UC SESM 80-3, STRUCTURES AND MATERIALS RESEARCH, UNIVERSITY OF CALIFORNIA, BERKELEY, 1980.

This is the third of a four volume sequence on the structural behavior of a two-span, four cell, box girder bridge model.

In the present volume, the structural behavior of the skew box girder bridge model during ultimate loading to failure is described and interpreted. Analyses of the flexural collapse mechanism and shear capacity are presented and compared with experimental results.

A comparison of the behavior of the skew bridge during ultimate loading with earlier tested straight and curved models is made. The possible design implications of the ultimate load behavior and the effects of skew on the response are discussed.

136. SCORDELIS,A.C., BOUWKAMP,J.G., WASTI,S.T., ANICIC,D., **"STRUCTURAL BEHAVIOR OF A SKEW TWO SPAN REINFORCED CONCRETE BOX GIRDER BRIDGE MODEL (VOL.4)"**, UC SESM 80-4, STRUCTURES AND MATERIALS RESEARCH, UNIVERSITY OF CALIFORNIA, BERKELEY, 1980.

This is the fourth of a four volume sequence. In the present volume detailed tables of experimental and analytical results obtained in a study of a large scale, skew, two-span, four cell, reinforced concrete box girder bridge model are presented. Results in terms of reactions, deflections, strains, and moments are given. The responses of the bridge to point loads, conditioning loads, and truck loadings, all at working stress levels, are tabulated. In addition, tabulated results are given for conditioning loads at overstress levels and for point loads after conditioning overloads.

137. SEIBLE,F., **"NONLINEAR ANALYSIS AND ULTIMATE STRENGTH OF MULTI-CELL REINFORCED CONCRETE BOX GIRDER BRIDGES"**, UCB/SESM-82-02, STRUCTURAL ENGINEERING AND STRUCTURAL MECHANICS, UNIVERSITY OF CALIFORNIA, BERKELEY, 1982.

This paper presents an analytical model to trace the nonlinear response of multi-cell reinforced concrete box girder bridges under stepwise increasing static loads. The only nonlinearities considered are material nonlinearities inherent in reinforced concrete structural members under short term loading, such as cracking of concrete, yielding of reinforcement, and formation of plastic hinges due to flexure and shear.

The analytical model, based on a three-dimensional grillage, is developed for multi-cellular structures of arbitrary plan geometry and constant height. This analytical method is capable of tracing the complex nonlinear behavior of the bridge beyond the working stress range all the way up to the ultimate failure and collapse of the structure. The collapse mechanisms and failure loads can be determined.

The proposed analytical scheme which is based on a mixed model formulation is demonstrated and tested on a series of numerical examples. The results are compared with experimental results obtained from large scale tests on multi-cell reinforced concrete box girder bridge models.

138. SIESS,C.P., VELETSOS,A.S., **"DISTRIBUTION OF LOADS TO GIRDERS IN SLAB AND GIRDER BRIDGES : THEORETICAL ANALYSES AND FIELD TESTS"**,HIGHWAY RESEARCH BOARD NO.14, PP. 58-74.

The object of the paper was to present a picture, based on theoretical analyses, of the manner in which loads on slab and girder highway bridges are distributed to the supporting girders. The discussion is restricted to simple span right bridges consisting of a slab of constant thickness supported on five girders spaced equidistantly and having equal flexural stiffnesses but no torsional stiffness.

The paper identifies the different variables involved in calculating the lateral distribution of loads and explains the importance of each. Later assumptions are made, and load and moment distributions are studied. The most significant variables discussed are as follows:

1. The effect of relative stiffness (slab to girder). Influence lines are presented for a five girder structure at midspan.
2. Effect of Ratio b/a (ratio of girder spacing to span).
3. Effect of loading.
4. Effect of diaphragms.

138A. SIESS,C.P., VIEST,I.M., **"TESTS OF CONTINUOUS RIGHT I-BEAM BRIDGES"**, UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION BULLETIN NO. 416, 1953.

Three 1:4 scale models of two-span continuous bridges were tested for the purpose of obtaining experimental evidence concerning the distribution of moments and strains and the effects of composite action

on the behavior of such bridges. Each bridge consisted of five steel I-beams and a mortar slab resting on the top of the beams. In two bridges, the slab was tied to the beams with channel shear connectors; in the third bridge no connection was provided between the beams and the slab. The specimens, methods of testing, and test results have been described in detail, and the experimental data compared with the results of the tests of simple span bridges (Bulletin 363). The important test results are discussed and summarized.

139. TAYLOR,R., HOLOWKA,M., **"LOAD TESTING AND EVALUATION OF A CONCRETE RIGID FRAME BRIDGE - THE CPR OVERHEAD BRIDGE (SITE 46S 123)"**, 78-SRR-2, RESEARCH AND DEVELOPMENT DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, 1978.

The paper describes the load testing, analysis, and evaluation of a three-span rigid frame concrete bridge. The bridge was tested with a gross test vehicle weight of 155 kips (maximum tandem axle load of 71.5 kips).

Due to problems regarding the middle span and also because the end spans were longer, one of the end spans was tested. Transducers were positioned so that their locations would correspond with the nodal coordinates of the finite element idealization of the bridge. From the uniform distribution of transducers, experimental transverse and longitudinal influence lines were obtained.

Preliminary analysis was carried out using the MTC frame program which assumes a cracked section, and subsequently a two dimensional finite element analysis was performed using BR 01200 finite element program. To get an upper and a lower limit for the test results, the deck abutment interface was assumed to act both as a fixed-support and as simply-supported. The effects of edge stiffening due to curbs, sidewalks, and railings were ignored.

The test was performed by implementing 7 different static loadings. Column strains were measured by Demac strain gages. The results are tabulated as live load moments and deflections. The location of the transducers and finite element idealization and different loading cases are graphically presented. Also, test results are presented as moment-deflection diagrams at various sections.

The results were within estimated values but invariably on the conservative side. The section behaved as a non-cracked section.

140. TAYLOR,R.J., CSAGOLY,P.F., **"TRANSVERSE POST-TENSIONING OF LONGITUDINALLY LAMINATED TIMBER BRIDGE DECKS"**, RR220, RESEARCH AND DEVELOPMENT DIVISION, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, 1979.

The report describes the application of transverse post tensioning to an existing longitudinally nailed-laminated timber deck structure (Herbert Creek Bridge).

A computer analysis was performed using "ORTHOP" program which assumes that the transfer of load is performed by shear alone, with no transverse flexural stiffness. Later, the results were checked for location using influence lines.

The report provides a detailed description of the post-tensioning process design and installation. The correlation between the computer analysis and test results was reasonable in terms of pattern, but fair in terms of numbers. Reduction of assumed transverse rigidity yielded better results.

141. TEXAS HIGHWAY DEPARTMENT RESEARCH COMMITTEE, **"LOADING TESTS OF A REINFORCED CONCRETE SLAB-BRIDGE OF 25 FOOT SPAN"**, TEXAS HIGHWAY DEPARTMENT BRIDGE DIVISION, NOVEMBER 1946.

This paper presents the results of a series of load tests and the measurement of resultant strains in a reinforced concrete slab bridge. The primary objective of this test was to investigate the behavior of a full-scale slab built under typical bridge construction conditions and to compare the observed stresses with the theoretical stresses derived by the Illinois "Simplified Method".

Results showed that the stresses derived in accordance with the simplified method of design, as set forth in the University of Illinois Bulletin No. 346, compared with reasonable accuracy with the experimental stresses. In addition, the tests revealed that curbs were under designed in proportion to the slab and that a better balanced design can be attained by widening the curbs, adding one more bar of compression steel in each curb, reducing the thickness of the slab at curbs, and reducing the amount of transverse steel.

142. THARMABALA,T., **"STRUCTURAL EVALUATION AND LOAD TESTING OF FLACK BRIDGE, MITCHELL'S CREEK"**, SRR-84-08, RESEARCH AND DEVELOPMENT BRANCH, ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS, DOWNSVIEW, ONTARIO, 1984.

This report describes the structural evaluation and live load test studies performed on Flack River Bridge. The bridge consists of Pony trusses spanning

about 70 ft. with concrete deck cast over stringers and floor beams.

The evaluation was done according to Ontario Highway Bridge Design Code (OHBDC) Section 14 simplified method. Calculated floor beam moments were much higher than measured values but were reasonably close when correction was made for load sharing (using Bakht and Jaeger's methodology).

143. THOMAS,F.G., **"INVESTIGATION ON BRIDGE DECK SYSTEMS"**, INTERNATIONAL ASSOCIATION OF BRIDGE AND STRUCTURAL ENGINEERING (IABSE) PUBLICATIONS VOL.9, PP.45-59, 1949.

This paper reports on research work being done in connection with modern steel and concrete bridge deck systems. Three types of studies have been done:

1. A series of steel joists supporting a reinforced concrete slab.
2. Similar to no. 1, except that the joists are encased in concrete, and concrete jack arches span between the joists to support the slab.
3. A filler joist system with the steel joists completely encased in the concrete slab.

Tests were done on actual bridges and bridge deck systems in laboratory, and a mathematical analysis was made. These tests have shown that a considerable degree of lateral distribution exists even when the concrete slab has cracked. Also, even when a slab is cast on top of uncased steel joists without mechanical anchorage to aid the interaction of the steel and concrete, friction is sufficient to induce appreciable composite action.

144. THOMPSON,D.M., **"LOADING TESTS ON HIGHWAY BRIDGES - A REVIEW"**, TRANSPORT AND ROAD RESEARCH LABORATORY (TRRL), LABORATORY REPORT 1032, CROWTHORNE, BERKSHIRE, ENGLAND, 1981.

The paper is a review of the tests performed during the past decade. The tests performed are classified in three major groups : acceptance tests, assessment of load carrying capacity, and research and development in support of design.

The paper provides general guidelines for testing and, it provides a useful list of the major tests performed in the past decade.

145. THOMPSON,J.T., **"MODEL ANALYSIS OF REINFORCED CONCRETE ARCH"**, PUBLIC ROADS, VOL.9, NO.11, 1929.

This paper presents a comparison of the measured and computed deformations of a reinforced concrete arch bridge under live load with deformations as determined by the use of an elastic model of sheet celluloid and Beggs deformeter gages. In the previous report (Public Roads no.10), the model analysis on the Yadkin River Bridge in North Carolina was not expressed in detail, and only the results are given. This paper presents a detailed description of the procedure, an explanation of the problems encountered, and the manner in which these problems were solved.

It was found that the behavior of the free arch rib as calculated by elastic theory is in close agreement with that determined by the model analysis. However, considerable care must be exercised to maintain a fairly uniform room temperature during operations of the model.

146. VANHORN,D.A., **"STRUCTURAL BEHAVIOR CHARACTERISTICS OF PRESTRESSED CONCRETE BOX-BEAM BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 315.8, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, DECEMBER 1969.

This paper summarizes the results of five in-service field tests of spread box beam bridges. The main emphasis of the tests was the determination of lateral distribution of vehicular loads, and on beam deflections. The load distribution factors obtained from the tests were compared with values used in the design and with values derived from a procedure recommended by Sanders and Elleby.

Based on the investigation, it was recommended that consideration be given to revision of the current AASHO and Pennsylvania Department of Highways (PDH) procedures for load distribution in spread box-beam bridges.

147. VANHORN,D.A., **"FINAL REPORT - DEVELOPMENT AND REFINEMENT OF LOAD DISTRIBUTION PROVISIONS FOR PRESTRESSED CONCRETE BEAM AND SLAB BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 387.5, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, NOVEMBER 1980.

This paper was the final report on the research investigation entitled "Development and Refinement of Load Distribution Provisions for Prestressed Concrete Beam-Slab Bridges". The report included:

1. The main body of the original research report.
2. The results from the project.
3. A summary relating the results to the objectives of the project.

148. VANHORN,D.A., CHEN,C.H., **"STRUCTURAL BEHAVIOR OF A PRESTRESSED CONCRETE I-BEAM BRIDGE - LEHIGHTON BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 349.4, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, OCTOBER 1971.

This paper describes the field testing of an in-service prestressed concrete I-beam bridge with stay-in-place corrugated steel sheet deck forms. The bridge consisted of three simply supported spans, each 71.5 ft. center to center of bearings, with a 90 deg. skew. A vehicle simulating an HS20-44 vehicle was driven in specified lanes at speeds of crawl up to 60 mph., and at 10 mph. over a 2" ramp to simulate a severe impact condition.

Results revealed that the load distributed to the interior beams was less than design values while the load distributed to the exterior beams under curb section was greater than the design value. Midspan diaphragms only slightly influenced the experimentally-based distribution factors at multi-lane loading, but did serve to distribute the load more evenly for a single vehicle load.

148A. VIEST,I.M., **"REVIEW OF RESEARCH ON COMPOSITE STEEL-CONCRETE BEAMS"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.86, NO.ST6, JUNE 1960.

This paper describes the investigations of composite beams carried out in the period 1920-1958 in the United States and abroad including both experimental and theoretical studies. Tests of specimens with and without mechanical fasteners are summarized, specimens briefly described, and major results cited. Presentation of theoretical studies emphasizes the basic assumptions of both elastic and ultimate strength theories.

148B. VIEST,I.M., CHAIRMAN, **"COMPOSITE STEEL-CONCRETE CONSTRUCTION, BY THE SUBCOMMITTEE ON THE STATE-OF-THE-ART SURVEY, OF THE TASK COMMITTEE ON COMPOSITE CONSTRUCTION, OF THE COMMITTEE ON METALS, STRUCTURAL DIVISION"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.100, NO.ST5, MAY 1974.

The report consists of a text and a supporting bibliography. For each subdivision of the text there is a corresponding, self-contained section in the bibliography. The report presents the current (1973) state-of-the-art so the bibliography is limited to recent references. For earlier references the reader is referred to Viest's 1960 review of research on composite beams, to Stevens' 1965 study of encased columns and to Gardner and Jacobson's 1967 paper on concrete filled steel tubes.

The report includes the following sections: Strength of shear connectors in normal and lightweight concrete; composite beams and girders with a homogeneous steel I cross section and a solid cast-in-place slab; other types of composite beams and girders; concrete encased steel beams; composite slabs, plates and shells; beam-to-column and beam-to-girder connections; steel-concrete composite columns; composite buildings; composite bridges; and concluding remarks.

148C. VIEST,I.M., FOUNTAIN,R.S., SINGLETON,R.C., COMPOSITE CONSTRUCTION IN STEEL AND CONCRETE, McGRAW-HILL, NEW YORK, 1958.

This is one of the earliest text written on the subject of designing composite beams. Because composite bridges are more common than composite construction for buildings, more emphasis is placed in this text on bridge design. The chapters in this text include Basic Concepts in Composite Design, Composite Beams, Shear Connectors, Design of Composite Beams and Shear Connectors, Design Aids and Literature.

148D. VIEST,I.M., SIESS,C.P., APPLETON,J.H., NEWMARK,N.M., **"FULL-SCALE TESTS OF CHANNEL SHEAR CONNECTORS AND COMPOSITE T-BEAMS"**, UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION BULLETIN NO. 405, 1952.

The primary objectives of the full-scale tests reported in this bulletin were to investigate the behavior of composite steel and concrete T-beams and the behavior of channel shear connectors used in such beams.

Four composite steel and concrete T-beams with channel shear connectors were tested on simple spans of 37.5 ft. by applying single concentrated loads at the center line and at other points. These beams were designed according to the AASHO specifications for H-20 loading. Individual channel shear connectors were investigated with the aid of 43 push-out tests. The description of specimens, their manufacture and testing, and the test results have been presented in detail in this bulletin.

148E. VORA,M.R., MATLOCK,H., **"ANISOTROPIC SKEW PLATES AND GRIDS"**, JOURNAL OF THE ENGINEERING MECHANICS DIVISION, ASCE, VOL.105, NO.2, APRIL 1979, PP.237-253.

A discrete element approach is presented which was used to analyze anisotropic skew slabs and grids. The method allows for varied stiffnesses, loads and supports. The distinguishing feature is that it also solves a variety of other problems. This paper also gives example problems with data comparisons.

149. WALLACE,M.W., **"STUDIES OF SKEWED CONCRETE BOX GIRDER BRIDGES"**, TRANSPORTATION RESEARCH RECORD 607, TRANSPORTATION RESEARCH BOARD, WASHINGTON D.C., 1976.

This paper presents the results of a study to describe the behavior of skewed box-girder bridges, and to suggest design criteria. Analysis of 51 mathematical models using the finite element analysis program CELL was used to assess the effects on structural behavior of varying superstructure width to span length (aspect) ratio, number of cells, skew angle, type of loading, and depth.

Span length and skew angle were found to be the most significant parameters influencing girder shear distribution. Aspect ratio and skew angle affected longitudinal bending moments to the largest extent. Based on the results of this study, methods for shear and bending design of skewed bridges are presented.

150. WARWARUK,J., SOZEN,M.A., SIESS,C.P., **"STRENGTH AND BEHAVIOR IN FLEXURE OF PRESTRESSED CONCRETE BEAMS"**, UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION BULLETIN NO. 464, 1962.

This bulletin summarizes and presents the information on the flexural strength and deformation characteristics of prestressed concrete beams acquired in the course of the investigation of prestressed reinforced concrete for highway bridges which had been in progress since 1951. The main contents of this paper are as follows :

1. Presentation of a general analysis for the flexural strength of prestressed concrete beams.
2. Development of procedures for the determination of flexural deformations of prestressed concrete beams at various stages of loading.
3. Description of test results of prestressed concrete beams failing in flexure.
4. Development of simple approximate methods for the determination of the flexural strength of prestressed concrete beams.

151. WEGMULLER,A.W., **"OVERLOAD BEHAVIOR OF COMPOSITE STEEL-CONCRETE BRIDGES"**, JOURNAL OF THE STRUCTURAL DIVISION, ASCE, VOL.103, NO.ST9, SEPTEMBER 1977, PP. 1799-1819.

This report describes the application of finite element techniques for finding the elastic-plastic response of composite steel-concrete beam-slab type bridges. A test model bridge studied experimentally by Newmark, Siess, and Viest was chosen to verify the computer approach presented in this report. The study led to the following conclusions:

1. The program generates a great amount of information on strains, stresses, internal forces, and displacements as well as information on the state of concrete slab layers, reinforcing steel layers and beam steel layers. This information can be used in judging bridges subjected to overloads.
2. The assumptions made for the shear retention factor and the tensile strength of concrete only slightly affect the load deformation response of the bridge structure studied in this report.
3. Up to approximately 20% overload, the overall response of the structure can adequately be predicted using the assumption that the deck slab behaves in an elastic, perfectly plastic manner.

152. WEGMULLER,A.W., CORDOBA,G.C., VANHORN,D.A., **"SLAB BEHAVIOR OF A PRESTRESSED CONCRETE BOX-BEAM BRIDGE - HAZLETON BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 315A.2, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, FEBRUARY 1971.

This paper presents the results of field testing of a beam-slab type highway bridge constructed with prestressed concrete box-girders and subjected to loading with a test vehicle simulating an HS20-44 loading. In general, the test structures responded predictably to lateral variation in load position. Experimentally found transverse bending moments, neglecting local effects, were found to be smaller than design values prescribed by AASHO specifications. It was observed that superposition of single truck response to determine the response of multiple trucks was valid only for an uncracked slab. For this bridge the superposition resulted in experimental slab bending moments which were generally less than the AASHO design value.

153. WEGMULLER,A.W., VANHORN,D.A., **"SLAB BEHAVIOR OF A PRESTRESSED CONCRETE I-BEAM BRIDGE - BARTONSVILLE BRIDGE"**, FRITZ ENGINEERING LABORATORY REPORT NO. 349.3, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, MAY 1971.

This paper describes the field testing of the slab of a beam-slab highway bridge subjected to loading with a test vehicle simulating an AASHO HS20 load vehicle. The bridge was a multi-span, simply supported bridge consisting of a cast-in-place concrete slab supported by five precast prestressed concrete I-beams laterally spaced at 8 ft.

The results showed that experimental transverse bending moments were far smaller than the design values based on AASHO specifications. The superimposing of the results of single truck runs to determine the effects of a two truck loading was valid for an uncracked slab. In general, the test structures responded predictably to lateral variation in load vehicle position.

154. WILSON,W.M., KLUGE,R.W., COOMBE,J.V., **"AN INVESTIGATION OF RIGID FRAME BRIDGES. PART II: LAB TESTS OF REINFORCED CONCRETE RIGID FRAME BRIDGES"**, UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION BULLETIN NO.308, 1938.

This paper presents the results of laboratory tests done on two specimens of reinforced concrete rigid frames. Each specimen was designated as a highway bridge one and one-half feet wide, a span of 48 ft. center to center of the bases of the vertical legs, and a height of 16 ft. from base to top of deck. Specimen 2 was similar to specimen 1 except that the deck and legs contained shear reinforcement. It was found that shear reinforcement added to the ductility of the reinforced concrete rigid frame bridges tested, increasing the deformation to which they could be subjected without failure.

The analysis of a reinforced concrete rigid frame bridge by elastic theory was found to give values for the moment, thrust, and shear on any section which were accurate enough for purposes of design if the analysis was based on the following assumptions:

1. The stress-strain relation for the concrete had the same value at all sections and at all stresses.
2. The moment of inertia for an uncracked section was used.

155. WRIGHT,P.D., **"DESTRUCTIVE TESTING OF THE KARAKA CREEK BRIDGE"**, CENTRAL LABORATORIES REPORT NO. 5-81/1, CENTRAL LABORATORIES, GRACEFIELD, LOWER HUTT, NEW ZEALAND, 1980.

This paper reports on the destructive testing of a 30 ft. span bridge. Live load testing of the bridge with a vehicle of known weight was followed by hydraulic jack loading to destruction of 2 main beams and the concrete deck to determine the capacity and failure mode of the span and deckslab.

The main body of this report presents and discusses graphed results, while the appendices contain typical calculations, computer input for bridge model on STRUDL, a list of raw data (forces, deflections and strains), and a summary of the results from the computer analysis.

The testing showed the nominal simply supported span to be almost fixed at the ends and that the curbs and handrails carried a significant portion of the load.

155A. YAN,H.T., COMPOSITE CONSTRUCTION IN STEEL AND CONCRETE, ORIENT LONGMANS, INDIA, 1965.

The text of this book mainly derives from a series of articles on Composite Construction in Steel and Concrete written by the author and published in the Indian Concrete Journal between 1960 and 1963.

156. ZELL,J.B., BEAL,D.B., **"HIGH STRENGTH STEEL AS REINFORCEMENT FOR CONCRETE BRIDGES: FINAL REPORT"**, RESEARCH REPORT 25, ENGINEERING RESEARCH AND DEVELOPMENT BUREAU, NEW YORK DOT, ALBANY, NEW YORK, NOVEMBER 1974.

This report describes the live load and long term dead load behavior of two concrete bridges with high strength steel reinforcement. The report also summarizes eight years of deflection measurements and crack surveys.

157. ZELLIN,M.A., KOSTEM,C.N., VANHORN,D.A., **"STRUCTURAL BEHAVIOR OF BEAM-SLAB HIGHWAY BRIDGES - A SUMMARY OF COMPLETED RESEARCH AND BIBLIOGRAPHY"**, FRITZ ENGINEERING LABORATORY REPORT NO. 387.1, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, MAY 1973.

This paper was the first report on the research investigation entitled "Development and Refinement of Load Distribution Provisions for Prestressed Concrete Beam-Slab Bridges". This report included:

1. A review of the four recently completed Lehigh University research programs on the structural response of prestressed concrete beam-slab highway bridges of the spread box-beam and I-beam types.

2. Discussion of the general findings in these programs.

3. Up-to-date annotated bibliography containing references on the structural behavior, analysis, and design of beam-slab type highway bridges.

158. ZELLIN,M.A., KOSTEM,C.N., VANHORN,D.A., KULICKI,J.M., **"LATERAL DISTRIBUTION OF LIVE LOAD IN PRESTRESSED CONCRETE I-BEAM BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 387.2A, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, JUNE 1975.

The objective of this paper was to develop a refined method for the evaluation of live load distribution factors for right beam-slab bridges of the prestressed concrete I-beam type. This report included:

1. A structural analysis based on the finite element method, which described superstructure response to design-vehicle loading.

2. Comparison of structural analysis with results from the field tests of two in-service bridges.

3. The analysis of 219 bridges ranging in length from 30 to 135 ft. and in roadway width from 20 to 78 ft.

4. Equations for evaluating live load distribution factors for interior and exterior beams.

159. ZELLIN,M.A., KOSTEM,C.N., VANHORN,D.A., KULICKI,J.M., **"LIVE LOAD DISTRIBUTION FACTORS FOR PRESTRESSED CONCRETE I-BEAM BRIDGES"**, FRITZ ENGINEERING LABORATORY REPORT NO. 387.2B, LEHIGH UNIVERSITY, BETHLEHEM, PENNSYLVANIA, JANUARY 1976.

This paper describes the development of new specification provisions for the evaluation of live load distribution factors in beam-slab highway bridges supported by prestressed concrete I-beams. This study included:

1. A structural analysis, based on the finite element method which described bridge response to design vehicle loading.

2. Comparison of structural analysis with results from field tests of two in-service bridges.

3. The analysis of 150 superstructures ranging in length from 30 to 135 ft. and in roadway width from 24 to 72 ft.

4. Equations for evaluating live load distribution factors for interior and exterior beams.

Based on the results from this study, proposed new specification provisions for live load distribution were recommended for adoption.

APPENDIX C

CASE STUDIES—LATERAL LOAD DISTRIBUTION

Appendix C is not published in this report but is contained in the unedited agency final report and is available on a loan basis by writing to the NCHRP, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

APPENDIX D

UNINTENDED COMPOSITE ACTION IN BEAM AND SLAB HIGHWAY BRIDGES

INTRODUCTION

The subject in this appendix is the investigation of unintended composite action in beam and slab highway bridges. The beam and slab bridge is one of the most commonly constructed types of highway bridges. Although there have been many studies involving this type of bridge, there have been very few on the subject of unintended composite action. This study is limited to the type of bridge with a reinforced concrete slab supported by steel beams. In a beam and slab bridge system, the behavior of the deck-girder interface typically is directly related to the overall performance characteristics of the bridge. Historically, no consideration was given to the composite effect of the beam and slab acting together. The assumption was that the slab acts independently of the beams in resisting loads. This neglect was justified on the basis that the bond between the deck and the top of the beams could not be depended upon. However, the advent of welding made it practical to provide mechanical shear connectors to resist the horizontal shear which develops during bending. There is no question as to the structural superiority of a compositely built beam and slab bridge over that of a noncomposite counterpart.

There have been tests done in which composite action was found to develop in beam and slab bridges that were not compositely built. A noncompositely built beam and slab system is defined as one in which no shear connectors are attached to the beam to interact with the slab. It is the intent of the work presented in this appendix to study this phenomenon and to investigate the factors that could influence the existence of composite action in noncompositely built steel beam and concrete bridges based on the available literature and test reports.

REVIEW OF TESTS ON BEAM AND SLAB BRIDGES

This section contains a review of tests done on beam and slab bridge systems related to this study (NCHRP Project 12-28(8). For each test, the bridge is described briefly and the significant test results as related to unintended composite action are presented. The names of the authors are given for each case, and the number in the parentheses corresponds to the date of the test or the year in which the report is published.

Burdette and Goodpasture (1970) (Ref. 26)

One of the four full-scale bridges that was tested to failure by Burdette and Goodpasture was a noncomposite, three-span continuous, slab and steel beam bridge (designated as Bridge 4). A 7- in. slab was supported by four 27- in. steel rolled beams. Figure D-1 shows a cross section of Bridge 4. The ultimate load in the actual test was compared to the ultimate load computed with the AASHO specification and to a theoretical ultimate load considering the entire cross section as a wide beam.

Figure D-2 shows the load-deflection curve for Bridge 4. The computed load-deflection curve was first developed assuming no composite action of the girders and bridge deck. Observation of the actual test and resulting strain data indicated that a considerable degree of composite action did exist at load levels approaching the load that would cause yielding of the steel in the noncomposite bridge. Bond between steel and concrete and friction forces that developed at the steel-concrete interface were sufficient to develop forces that resulted in the girders and deck acting compositely. The average shearing stress at the steel-concrete interface was approximately 230 psi at a load of 500 kips. The load-deflection curve calculated on the basis of composite action in the elastic range matched the measured data almost perfectly up to a load near the capacity of the noncomposite bridge.

Kissane (1985) (Ref. 84)

Full-scale laboratory and field testing were performed to determine the restraint to elastic buckling of a steel beam sup-

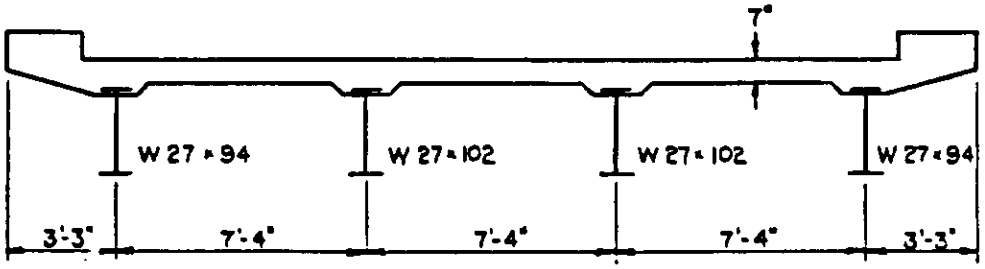


Figure D-1. Cross section of Bridge 4. (Ref. 26)

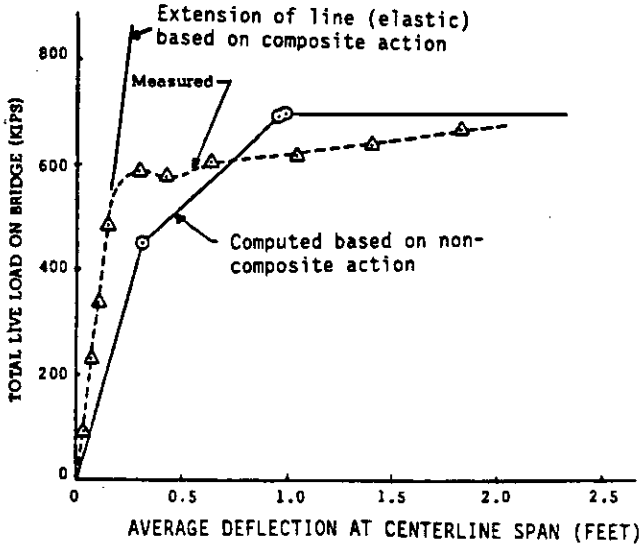


Figure D-2. Comparison of measured and computed load-deflection curves for Bridge 4. (Ref. 26)

porting a noncomposite concrete deck. In the laboratory tests, a 6-in. thick reinforced concrete slab was placed on top of an American Standard Beam. The test setup is shown in Figure D-3. Before pouring the concrete slab, the beam's top flange was sanded to remove mill scale and irregularities that could offer mechanical restraint at the concrete-steel interface. The flanges' bare metal surface was covered with a light oil to prevent chemical bonding between the concrete and steel.

The ratio of compression to tension flange strain was used as an indicator of composite behavior between the concrete and steel. Values of this ratio based on average flange strains are plotted versus applied load in Figure D-4. The average top and bottom flange strains are also shown. Experimental data show that there exists some amount of composite behavior and it increases as higher loads are applied. The amount of composite behavior translates to an approximately 10 percent increase in the bottom flange section modulus from a noncomposite value.

Since mechanical and chemical bond were inhibited between the steel and concrete, the partial composite behavior was attributed to friction between these components. As higher loads were applied, there is an increase in friction and pressure developed at the steel-concrete interface, thereby permitting increased composite behavior.

A field test was also done on a 146-ft simple span truss bridge built in 1924. Details of the structure are shown in Figure D-5. Two identically loaded haul trucks were used to load the bridge. Results showed that there was a small change in neutral axis position from that of a noncomposite section. However, the upward shift of 0.82 in. in the neutral axis position was considered insignificant due to the low magnitude of the measured stresses and the approximate 300 psi experimental error in the measurement. The author concluded that there was no significant evidence of composite behavior between the steel and concrete.

Bakht and Csagoly (1979) (Ref. 11)

An extensive diagnostic load test was undertaken to detect the sources of distress in the Perley Bridge, where in March 1973 a failure of the connecting angles of the girder-column connection of a trestle span caused the span to drop a few inches. One of the objectives of the diagnostic testing of the trestle span was to determine the degree of composite action that existed between the floor beams and the concrete deck slab in the absence of shear connectors.

Approximately 87 percent of the deck slab area was supported by girders and trusses through the floor beams. The test established that the composite action between the slab and the floor beams varied from beam to beam and could not be relied upon with certainty. Figure D-6 shows the moment diagrams obtained assuming noncomposite behavior and the actual moments obtained. Floor beam D carried 46 percent less than the load that it would have carried in the absence of any distribution of moment.

AASHO Road Test (1962) (Ref. 67)

The AASHO Road Test included a study of 18 beam and slab bridges. Each bridge was a simple span structure consisting of three beams and a reinforced concrete slab. The beams spanned 50 ft. Ten of these bridges had wide flange, rolled steel beams with or without coverplates. Two of the ten steel bridges were built compositely with shear connectors, while the other eight were noncomposite. Figure D-7 shows several typical bridge sections as used in the test. The top surfaces of the steel beams in the noncomposite bridges were coated with a 1:4.43 mixture of graphite and linseed oil to inhibit formation of bond. In composite bridges, the interaction between the slab and the

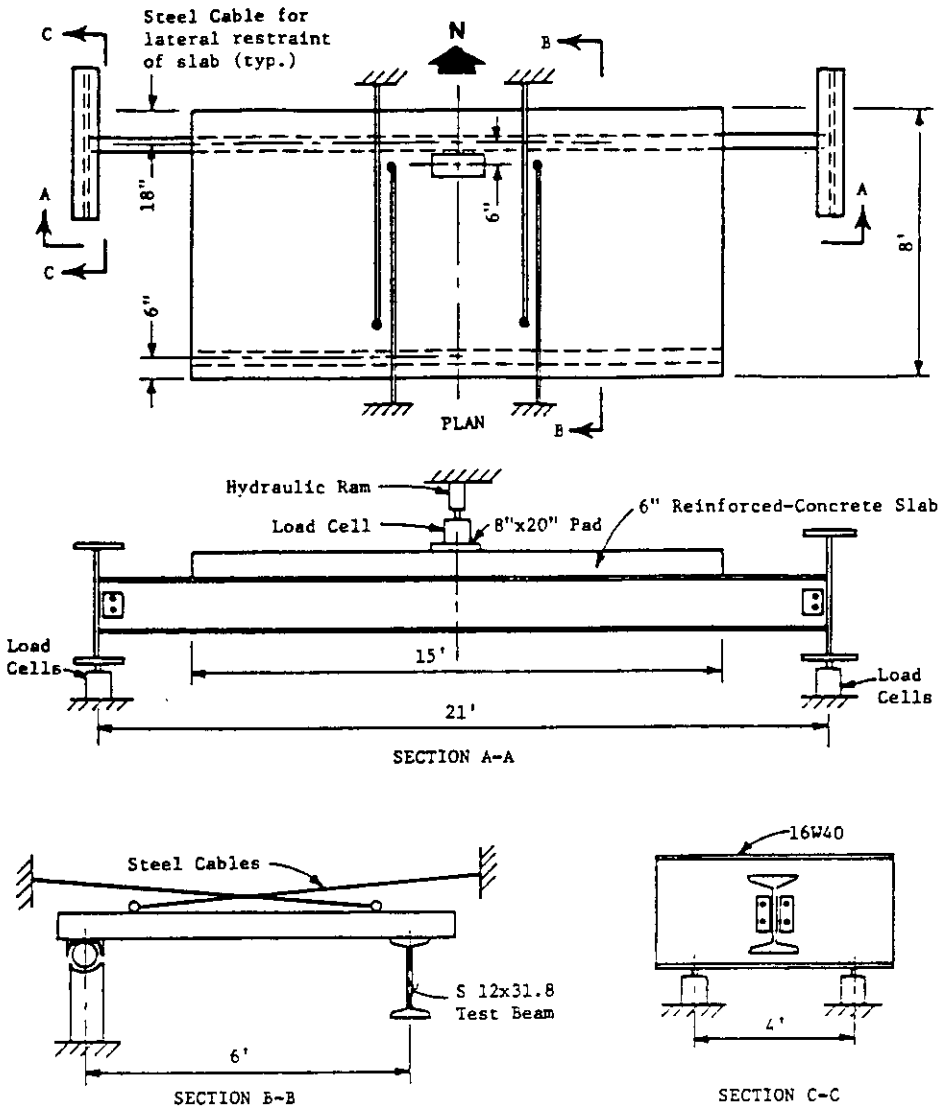


Figure D-3. Test setup. (Ref. 84)

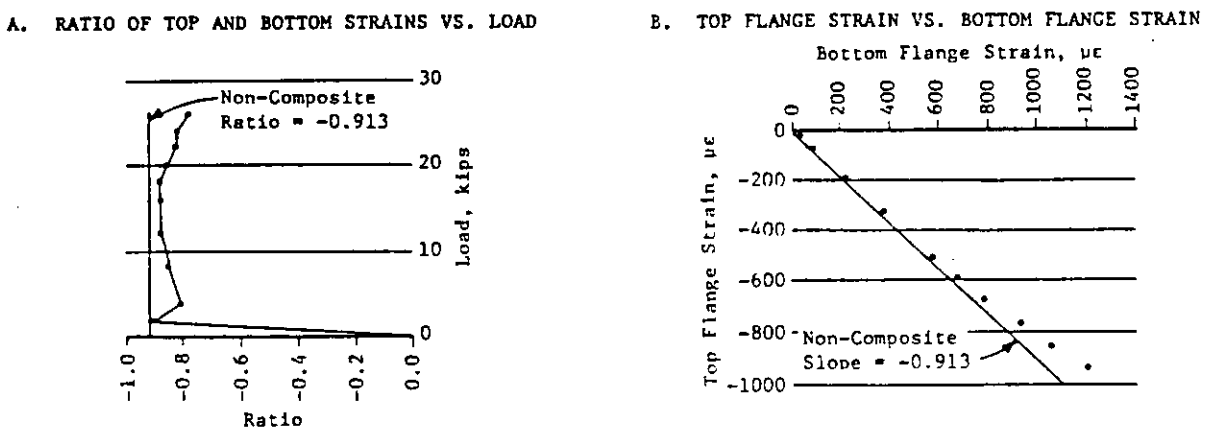


Figure D-4. Strain relationships. (Ref. 84)

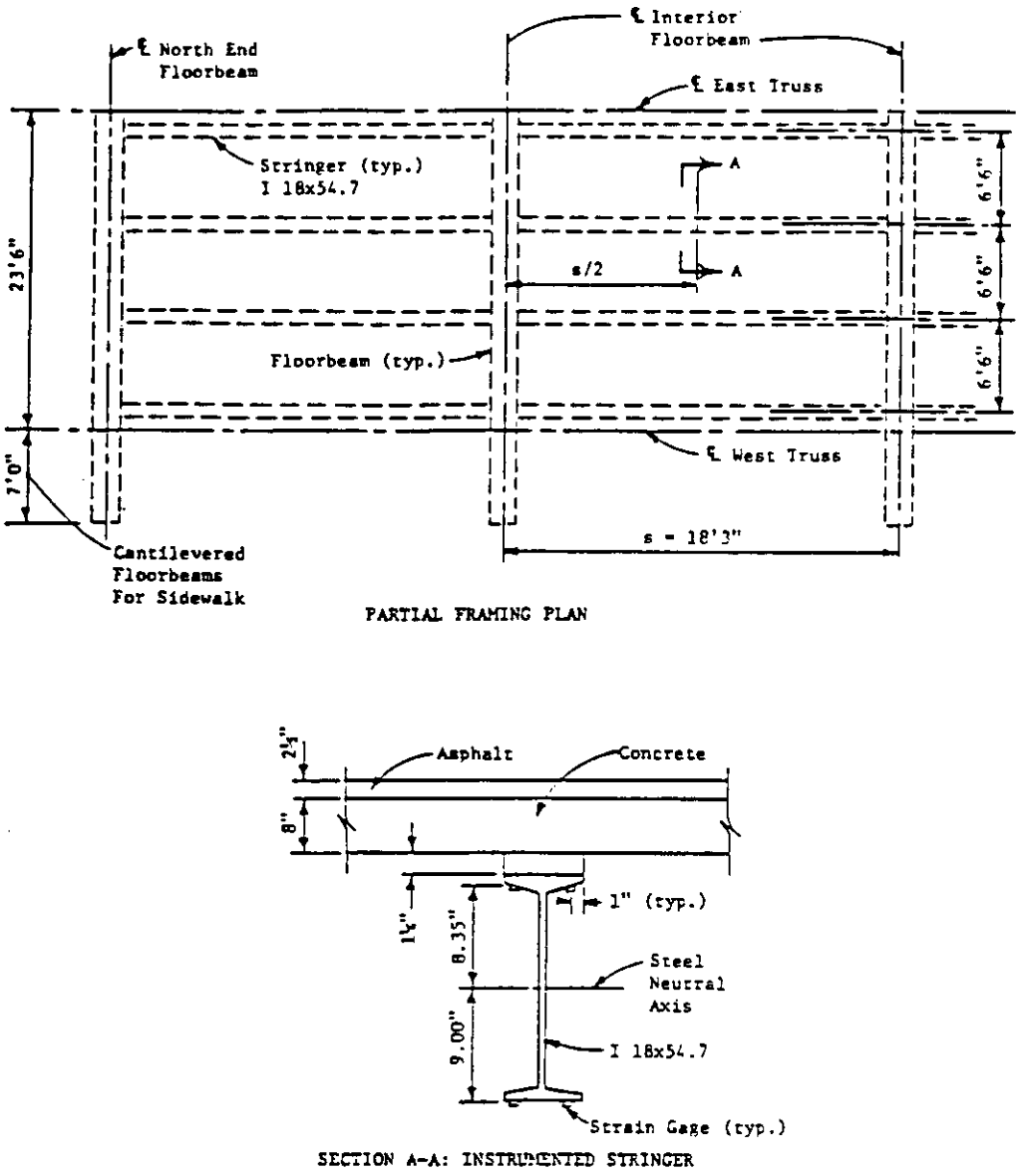


Figure D-5. Details of field-test structure. (Ref. 84)

steel beams was obtained with 4-in., 7.25-lb channels 5.5 in. long, welded to the top flanges.

In the design of the beams, two of the steel bridges were designed to have complete interaction between the slab and the beams, while six of the bridges were assumed to have 10 percent composite action to account for the effects of friction between the slab and the beams. No composite action was assumed for the remaining two bridges in the design.

After the bridges had been tested with repeated stresses, the actual locations of the neutral axes were determined from strains measured on the bottom and top of beams at midspan assuming straight line strain distribution. In calculating the theoretical location of the neutral axis, the compositely built steel bridges were considered as fully composite; for the other steel bridges a complete absence of interaction between the slab and the beams was assumed. Table D-1 gives the distance of the experimental location of the neutral axis from the theoretical value, which is a mean for all 30-mph runs within the 10-month observation period.

The difference between the measured and the theoretical location of the neutral axis was small, indicating that the bridges with mechanical connectors were fully composite, whereas the others had practically no composite action. The moment-deflection diagrams also showed a much stiffer section for the composite beams; for example, Bridges 1A and 3B had beams of the same depth, but for a midspan moment of 500 kip-ft the deflection at midspan for Bridge 1A was 2.2 in., whereas Bridge 3B had only 0.6 in. of deflection. The report concluded that there was no composite action present for the bridges with no shear connectors.

Thomas (1949) (Ref. 143)

A 1:3 scale model of a bridge deck system was tested to determine the extent of lateral load distribution of the system and the extent to which the steel joists and the concrete slab act together in resisting the induced bending moments. The model consisted of a reinforced concrete deck 3 in. thick, supported on six standard 8-in. by 4-in. longitudinal beams spaced at 3-ft centers, with the end beam being at the ends of the concrete slab. The slab was cast independently of the steel joist system to minimize bond induced by construction methods.

Load was applied to the model by means of a hydraulic jack. The tests were made in three stages: load applied to the slab in its uncracked condition, load applied to the slab after it had been systematically cracked, and final loading to failure.

For the test on the uncracked model, a comparative study of the strains measured in the upper and lower flanges of the beams showed that some partial composite action existed between the beams and the slab. The effect was more pronounced for beams near to the load, suggesting that composite action was primarily due to friction between the slab and the flanges of the beams.

For the test on the cracked model, a study of strain measurements indicated there was slightly less composite action between the beams and the slab as a result of cracking. The slab failed by punching shear at a load of 45.1 kips. The author concluded that shear connectors should be fixed to the joists if full allowance of composite action is to be made.

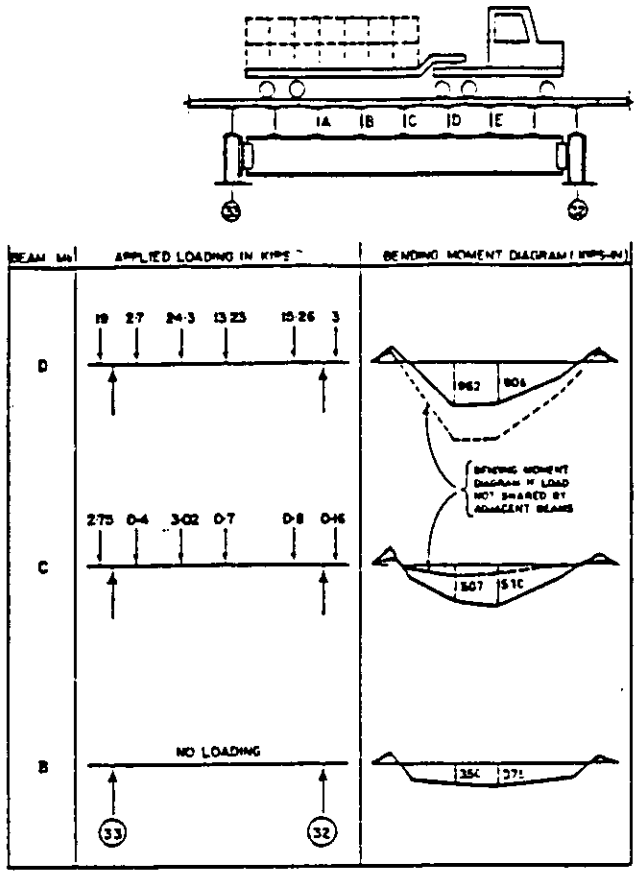


Figure D-6. Sharing of loads by adjacent floor beams (1 kip = 4.448 kN; 1 kip-in. = 0.113 kN-m). (Ref. 11)

Siess and Viest (1953) (Ref. 138A)

Laboratory tests were made on three 1:4 scale models of continuous right I-beam bridges. Each structure was a two-span right bridge consisting of five steel beams supporting a reinforced concrete slab. The bridges were labeled as N30, C30, and X30. Bridge N30 was a noncomposite bridge, Bridge C30 had shear connectors welded to the top flanges of the I-beams at regular intervals throughout the full length of the bridge, and Bridge X30 had shear connectors omitted in the negative moment region in the vicinity of the center pier. The top flanges of the beams for Bridge N30 were covered with a coating of wax to prevent bond between the slab and the beams. For bridges C30 and X30, the top surfaces of the beams were left in the as-rolled condition. All tests were made with one, two, or four pairs of concentrated loads simulating the rear axle loads of one or more trucks.

For the test on Bridge N30, it was observed that the bottom and top flange strains were practically equal, as shown in Figure D-8 for applied loads at midspan. This is an indication that there was no interaction between the slab and the beams. The test data are also in agreement with the calculated values. For the test on bridges C30 and X30, observation of strain data indicated the presence of composite action for both bridges as expected. Bridges X30 and C30 failed ultimately by punching of the slabs at a load of 10.4 kips while bridge N30 failed by buckling of the beams at a load of 8.49 kips, even though bridge N30 had larger size beams. On the basis of the test results, it was summarized that the behavior of Bridge N30 was of a truly noncomposite structure, and bridges X30 and C30 acted as composite structures.

Table D-1. Difference between experimental and theoretical location of neutral axis. (Ref. 67)

Bridge	Location of * Neutral Axis (inch)
1A, NC	0.0
1B, NC	+0.2
2A, NC	+0.1
2B, C	+0.2
3A, NC	+0.2
3B, C	-0.1
4A, NC	+0.2
4B, NC	-0.1
9A, NC	+0.1
9B, NC	0.0

NC - Non-Composite, C - Composite

* Plus sign indicates position above theoretical

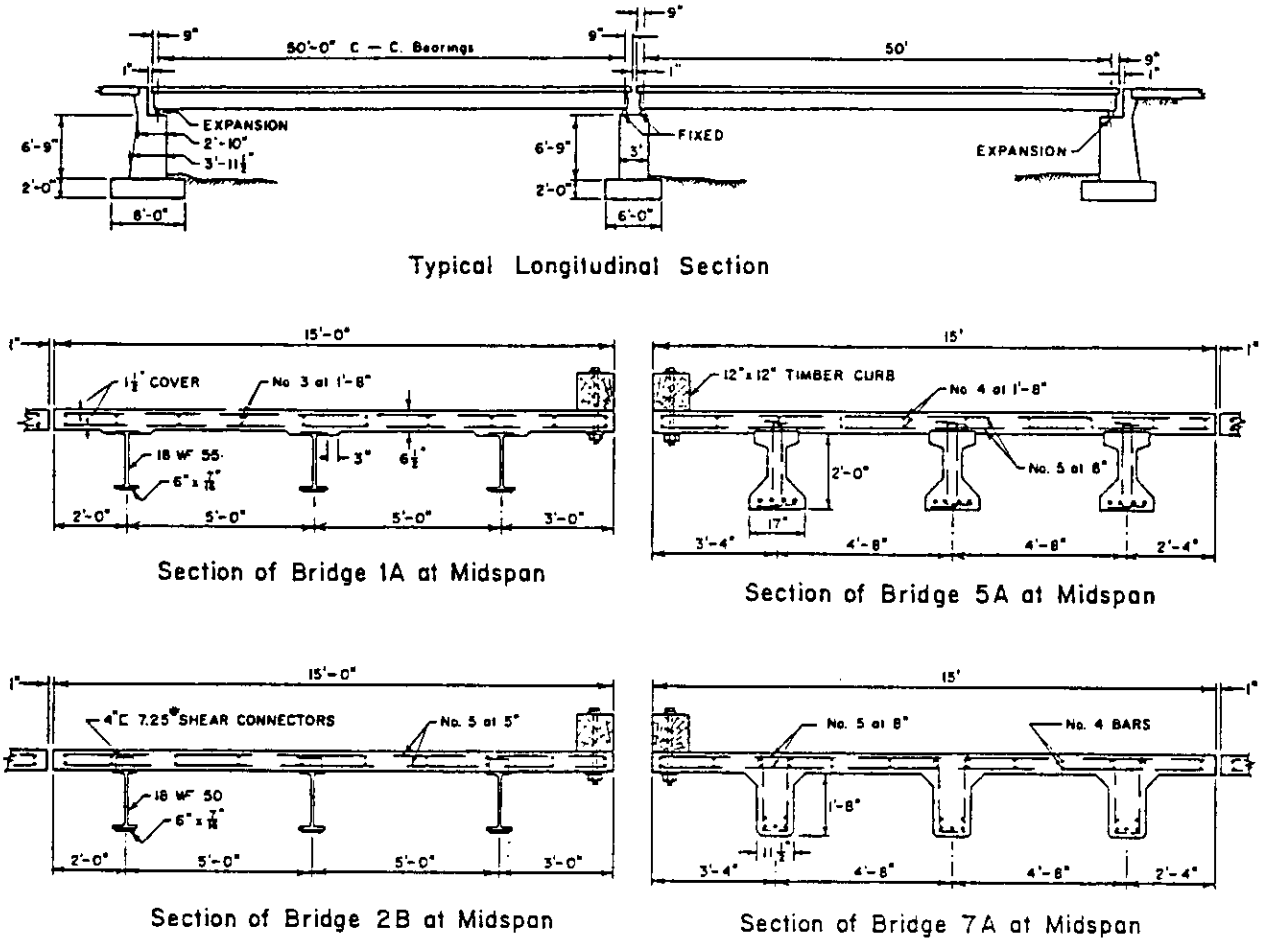


Figure D-7. Typical bridge sections. (Ref. 67)

Tharmabala (1984) (Ref. 142)

Structural evaluation and load test studies were performed on the Flack River Bridge, which is a bridge consisting of pony trusses spanning 70 ft with a concrete deck cast over stringers and floor beams. Figure D-9 shows the details of the bridge.

Two heavily loaded trucks were used to induce member forces to reach ultimate limit states defined by the *Ontario Highway Bridge Design Code* (OHBDC). Figures D-10a and D-10b show the stringer moments calculated using measured strains on the bottom flange with composite or noncomposite section properties as compared to the theoretical moments using grid analysis. Although the deck is of noncomposite construction, it can be observed that the measured moments obtained with composite section properties are closer to the theoretical moment graphs. Therefore, the deck behaves partially composite under the applied loads.

Patel (1984) (Ref. 109)

A structural evaluation and live load test were performed on Irvine Creek Bridge, which is a two-lane steel truss bridge with a sidewalk and two identical steel trusses spanning 104 ft over Irvine Creek. Figure D-11 shows a cross section of the bridge.

Two heavily loaded trucks were used for vehicular test loading. The stringer moments were calculated using grillage analysis of the deck under applied loading. Figures D-12a and D-12b show the corresponding test moments calculated using measured strains with composite and noncomposite section properties of the stringers versus theoretical stringer moments. Figure D-12a illustrates the loading cases of the trucks weighing approximately 175 kip and Figure D-12b illustrates that of a truck weighing 200 kip.

It can be observed from the figures that the graphs for the theoretical moment values lie between the graphs of the moments calculated using the fully composite and noncomposite section properties respectively. It indicates that the stringer sections are acting partially composite with the concrete deck.

From the strain data on the floor beams, it was observed that for each loading case the floor beam moments obtained from grid analysis compared very well with the measured moments using composite section properties. Even though the steel floor beams have been built to be noncomposite with the concrete deck, they have been found to act compositely since they have carried higher applied loads than the steel could have carried by themselves.

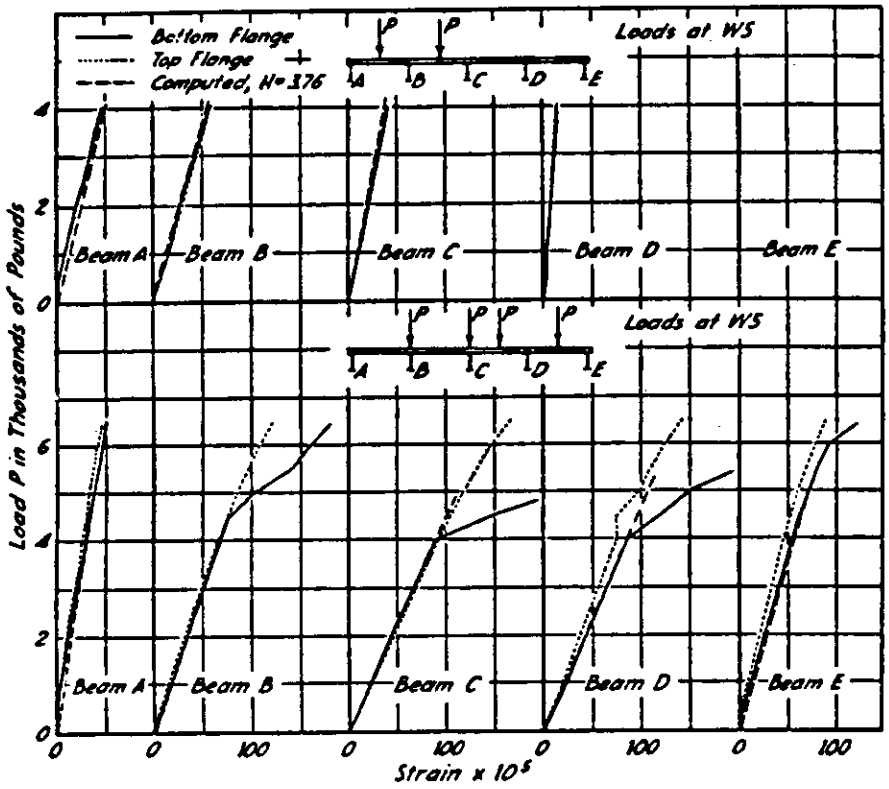
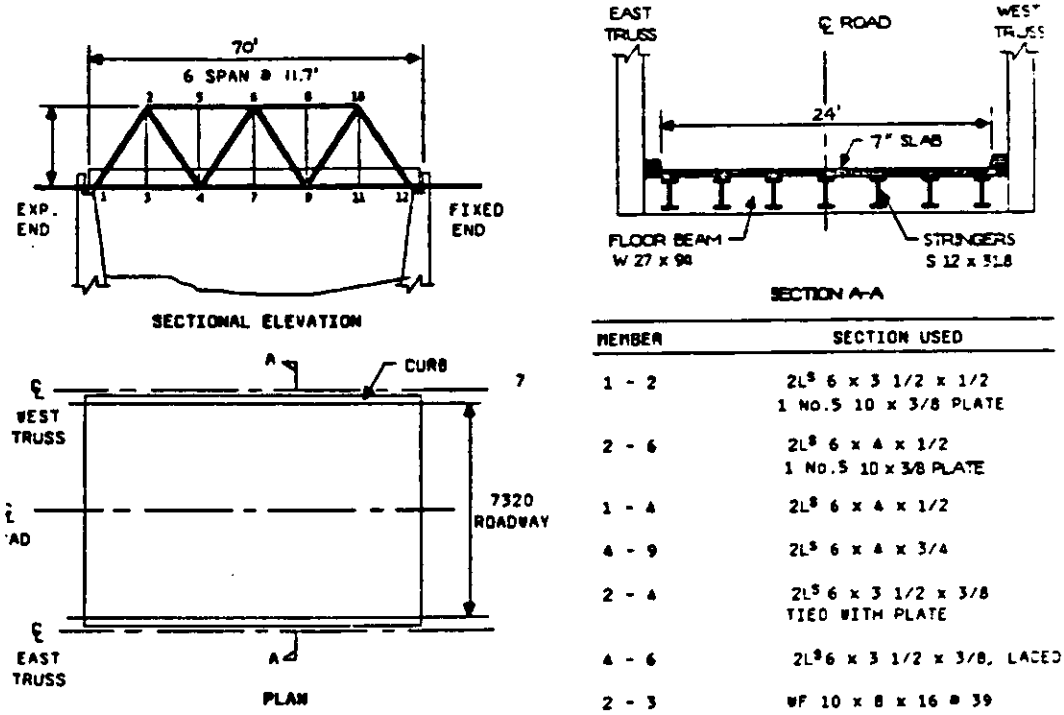


Figure D-8. Beam strains at maximum positive moment section, Bridge N30. (Ref. 138A)



MEMBER	SECTION USED
1 - 2	2L^S 6 x 3 1/2 x 1/2 1 NO.5 10 x 3/8 PLATE
2 - 6	2L^S 6 x 4 x 1/2 1 NO.5 10 x 3/8 PLATE
1 - 4	2L^S 6 x 4 x 1/2
4 - 9	2L^S 6 x 4 x 3/4
2 - 4	2L^S 6 x 3 1/2 x 3/8 TIED WITH PLATE
4 - 6	2L^{S}6 x 3 1/2 x 3/8, LACED
2 - 3	WF 10 x 8 x 16 @ 39

Figure D-9. Bridge details. (Ref. 142)

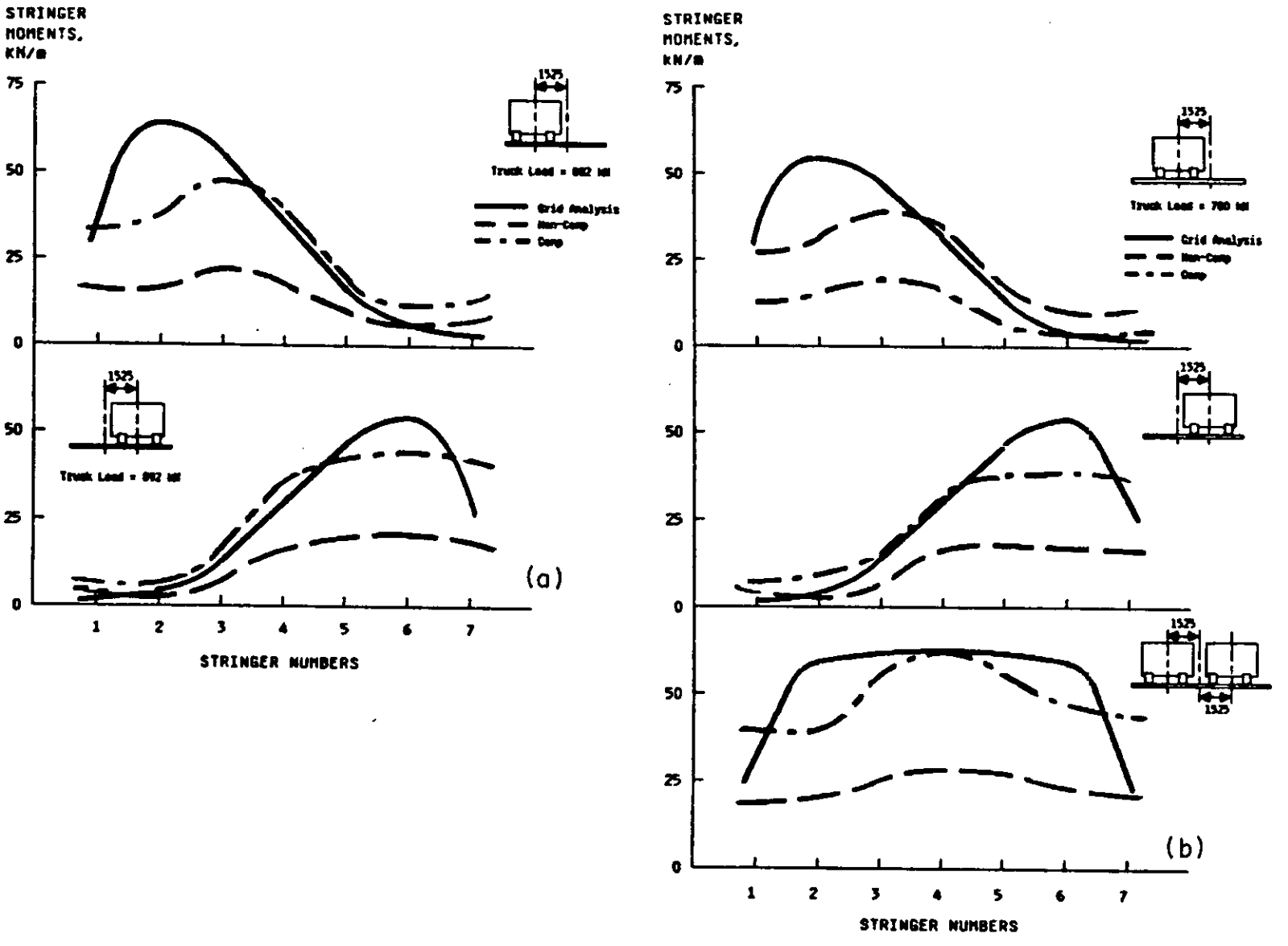


Figure D-10. Theoretical stringer moments related to measured stringer moments. (Ref. 142)

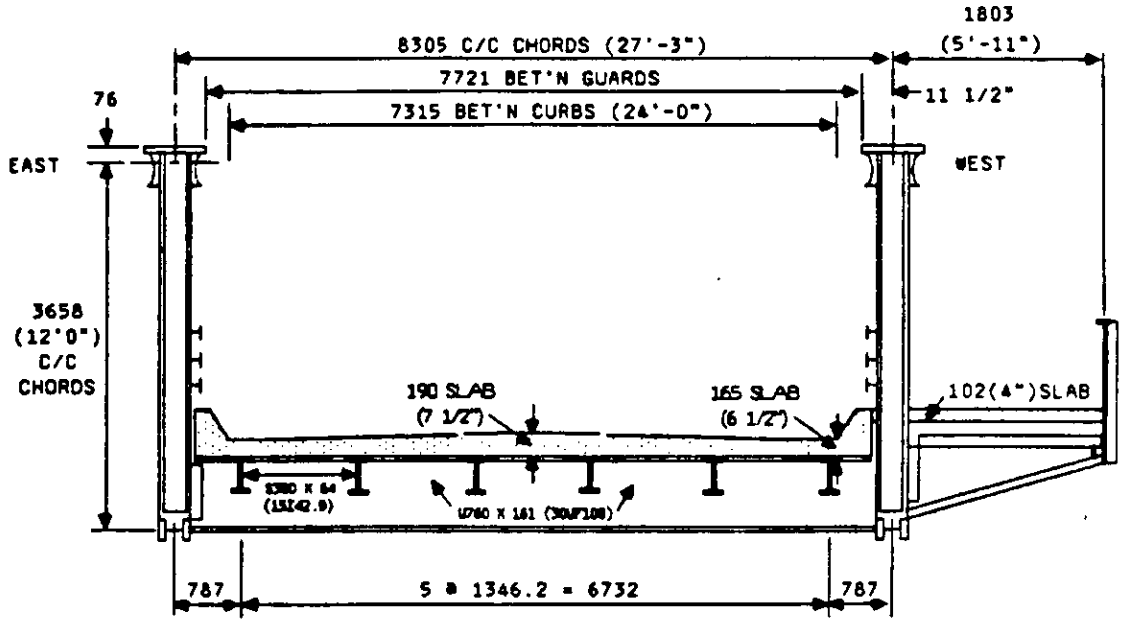


Figure D-11. Cross-section of Irvine Creek Bridge. (Ref. 109)

REVIEW OF TESTS ON BEAM AND SLAB SYSTEMS

This section contains a review of tests performed on beam and slab systems in which unintended composite action was observed. The tests reported in this segment deal with a single beam and slab as opposed to a multiple beam and slab bridge system in the first part of this appendix. A brief description of the test and the test results is presented for each case.

Viest, Siess, Appleton and Newmark (1952) (Ref. 148D)

Four composite steel and concrete T-beams with channel shear connectors were tested on simple spans of 37.5 ft by applying single concentrated loads at the centerline and at other points. In three of the beams tested, provision was made during construction to prevent bond between the slab and the steel beam to better observe the behavior of the shear connectors. However, one beam was allowed to develop natural bond in order to determine the effectiveness of bond in transmitting horizontal shear.

The results of the first test made with this beam revealed the presence of bond. Only after 11 repetitions of a load of 40 kips was the bond broken.

Figure D-13 shows that as long as bond is present, it proved to be an effective shear connection. Before bond was broken, there was practically no slip between the slab and the beam. The bond withstood a load equal to 1.7 times the design live load, corresponding to a shearing stress of 112 psi. The bond broke after the same load was applied 11 times. However, the researchers felt that if the static load had been increased instead of repeated, at loads approaching ultimate, large deformational bond stresses at the concrete-steel interface would have caused bond failure. Furthermore, shrinkage and warping of the slab as well as dynamic loading may destroy the bond even at working loads. It was concluded by the researchers that even though bond is a very good shear connection, it may also be an unreliable one.

Viest (1960) (Ref. 148A)

A review of research on composite steel-concrete beams was done by Viest on all tests carried out in the period between 1920 and 1958. Tests of specimens with and without mechanical shear connectors were summarized and briefly described. Practically every test that was done reached the conclusion that so long as bond between the concrete and the steel was not definitely broken, complete interaction between the slab and the beam can be assumed. Bond strengths between 400 and 500 psi were observed in some of the tests. However, it should be noted that most of these tests were pull-out tests on steel beams fully encased in concrete.

One of the first American tests was performed by Caughey (*30A*). Based on his test results and tests published prior to 1929, he recommended an allowable bond stress of 0.03 f'_c. Viest recommended an allowable bond stress of 60 psi when the steel beam is fully encased and 50 psi when the steel beam is only partially encased.

Bryson and Mathey (1962) (Ref. 24A)

An extensive test of bond between concrete and steel beams was performed by the National Bureau of Standards. Wide flange structural steel beams with different surface conditions were embedded in concrete and subjected to push-out tests to determine the effect of surface condition on the bond between

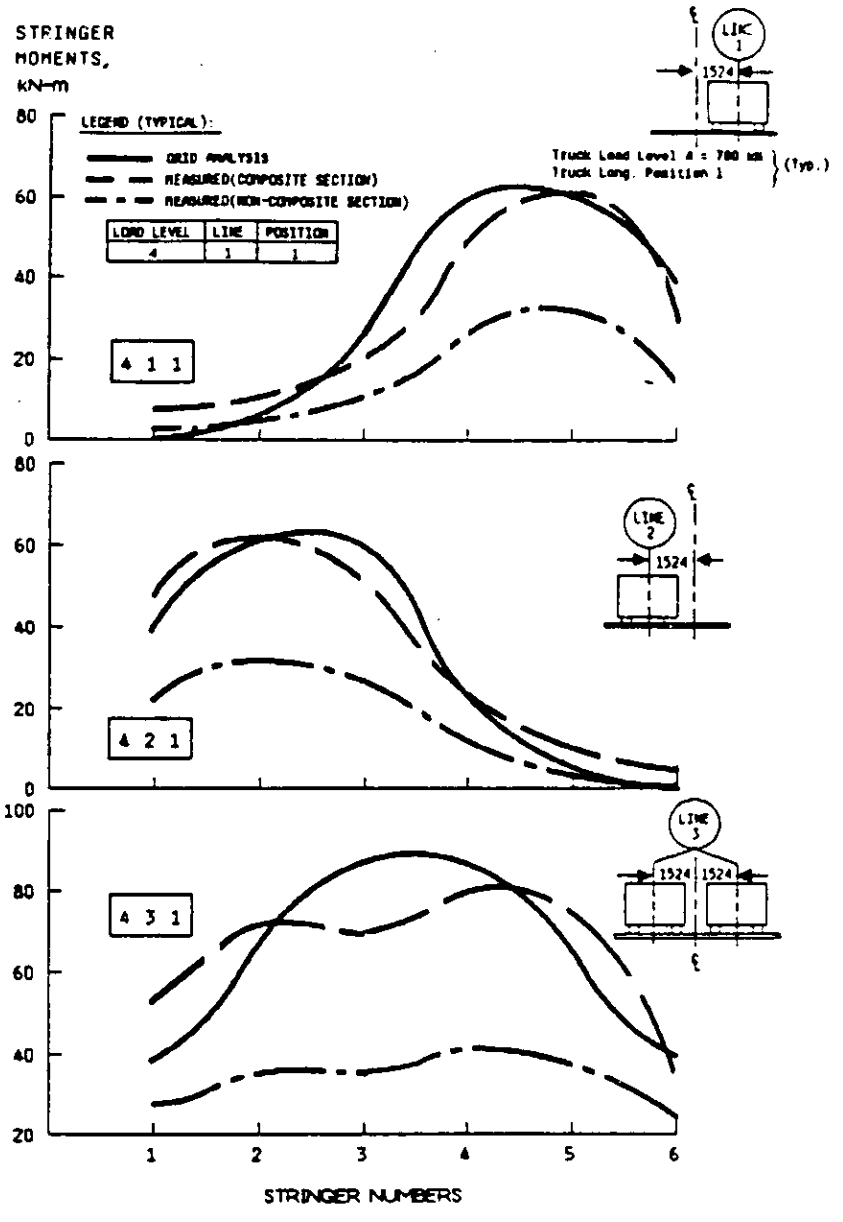


Figure D-12a. Stringer moments—load level 4 (175 kip). (Ref. 109)

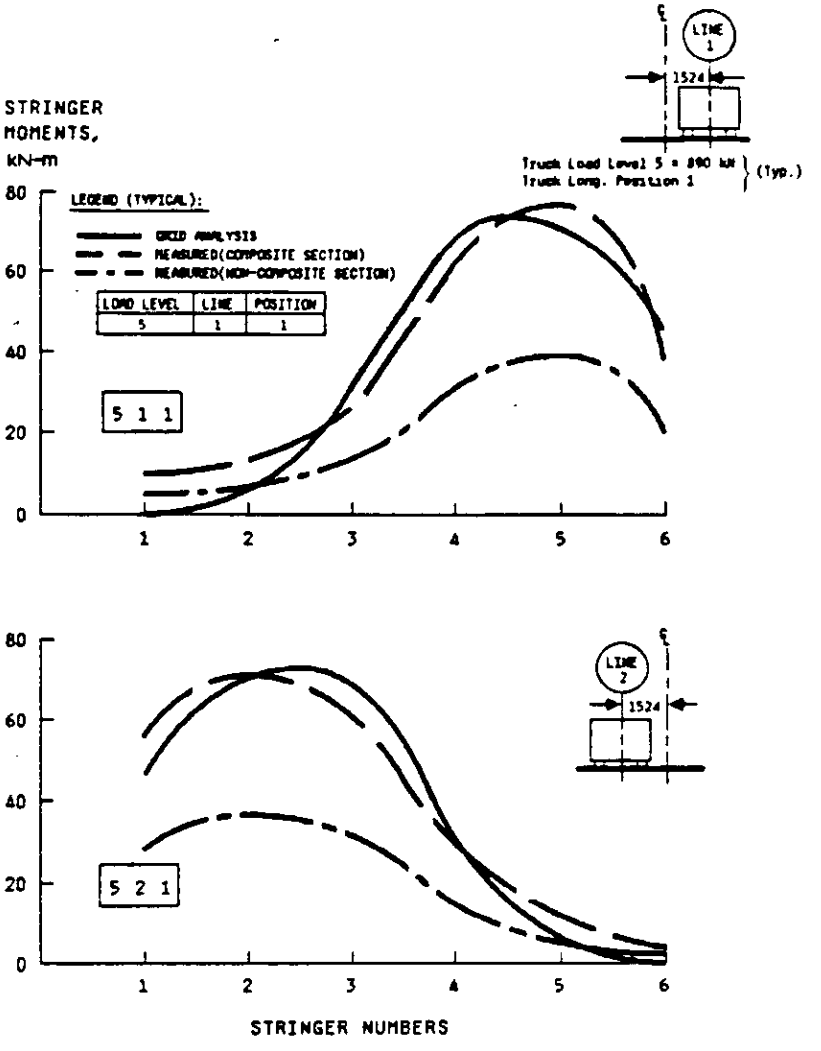


Figure D-12b. Stringer moments—load level 5 (200 kip). (Ref. 109)

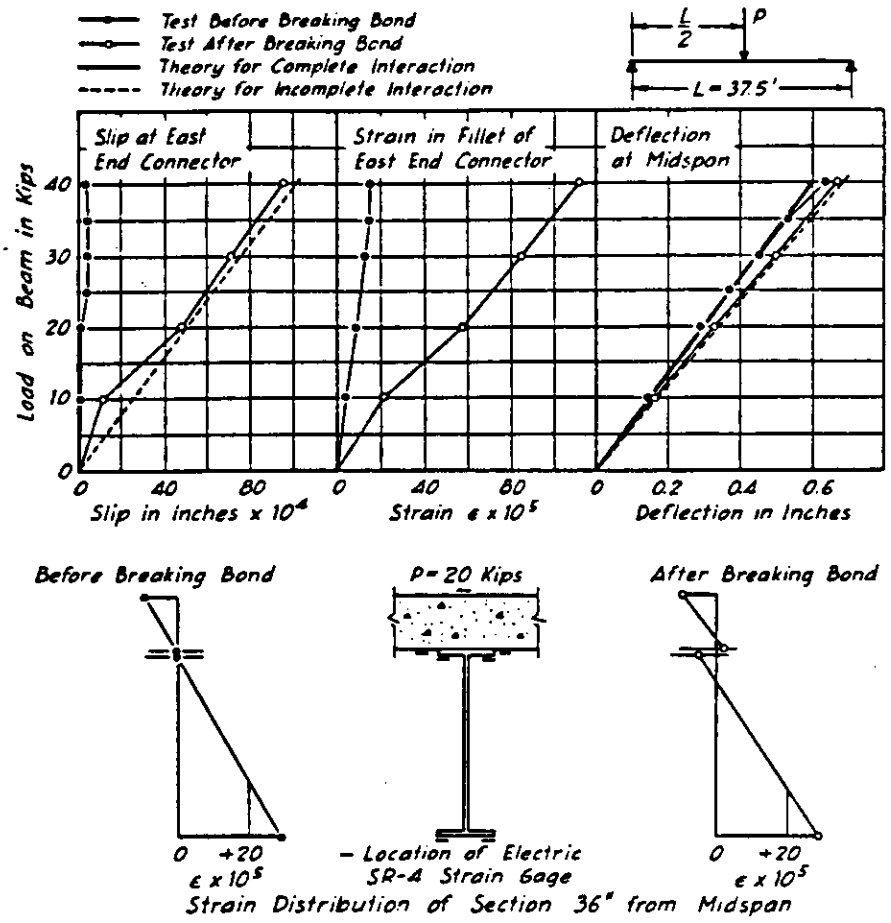


Figure D-13. Effect of bond on degree of interaction. (Ref. 148D)

concrete and steel. Three types of surface conditions were studied; normal rust and mill scale, sandblasted and allowed to rust, and freshly sandblasted steel sections. Three push-out specimens for each surface condition were constructed. The specimens were either W 14×30 or W 14×34 steel sections embedded in 2 ft of concrete. The bonded area of the steel beam was limited to the surface of the flanges.

A summary of the test results is given in Table D2. The results indicated a considerable difference in ultimate strength of the bonds. However, at low values of slip, bond stress was not greatly affected.

Table D-2. Summary of test results. (Ref. 24A)

Specimen	Steel Section	Surface Condition	Maximum bond stress, psi	Free end slip at maximum, inch
SB-1	14 WF 34	freshly sandblasted	420	0.015
SB-2	14 WF 30	"	474	0.008
SB-3	14 WF 34	"	470	0.006
Avg.			455	0.010
R-1	14 WF 30	sandblasted and allowed to rust	508	0.020
R-2	14 WF 34	"	403	0.018
R-3	14 WF 34	"	486	0.007
Avg.			466	0.015
N-1	14 WF 30	Normal rust and mill scale	310	0.003
N-2	14 WF 34	"	355	0.012
N-3	14 WF 30	"	287	0.002
Avg.			317	0.006

SUMMARY AND CONCLUSION

The fundamental purpose of this study was to investigate the phenomenon of unintended composite action and the factors which could influence the existence of composite action in noncompositely built steel beam and concrete bridge systems. Test reports mentioned earlier in this appendix have shown that the existence of natural or chemical bond is the single most important factor in determining whether a noncompositely built beam and slab system can be counted on to act compositely. Every reported test, be it full-scale or model, in which bond between the steel and concrete interface was prevented resulted in noncomposite behavior, with the exception of the laboratory test that was reported by Kissane. However, it should be noted that this particular test was done to study the lateral restraint of the beam, which is abnormal in the analysis of a beam and slab system. Caughey (*30A*) and Viest, Fountain and Singleton (*148C*) suggested allowable design bond stresses of 0.03 f'_c and 50 psi, respectively. Though not quantitatively stated, a large

factor of safety was implied in all design stresses. In the full-scale tests by Viest, Siess, Appleton and Newmark at Illinois (*148D*), the beam in which bond was not broken experienced full composite action at the maximum design load of 1.7 times the live load. The bond failed after 11 repetitions of the load. A horizontal shear stress of 112 psi was resisted by bond at this loading.

Even though bond has been shown to be very effective in transmitting horizontal shear, it is also unreliable because it is sensitive to fatigue loading, shrinkage, thermal stresses and impact. There is also the possibility of physical separation of the concrete slab and the steel beam due to uplift forces generated along the beam by certain dispositions of the live load (*155A*). These uplift forces may also contribute to the rapid deterioration of the natural bond at the steel-concrete interface. It was also stated by Viest, Siess, Appleton and Newmark (*148D*) that shrinkage and warping of the slab as well as dynamic loading may destroy the bond even at working loads.

Tests have also shown that composite action could also be induced by friction. However, the amount of friction which translates into a certain degree of composite action varies from one bridge to another depending on the weight of the deck slab, the magnitude of the load, and the surface roughness of the steel-concrete interface.

As a conclusion, even though certain beam and slab bridge systems have demonstrated the ability to act compositely without the use of mechanical shear connectors, the degree to which composite action can be counted on is very difficult to quantify because of the above variables. The contribution of unintended composite action should be regarded as a bonus, because it was not designed to exist in the first place.

APPENDIX E

EFFECTS OF DETERIORATION IN THE ASSESSMENT OF THE LOAD-CARRYING CAPACITY OF A BRIDGE

One of the major problems encountered by bridge inspectors in evaluating the load-carrying capacity of existing bridges is quantifying the effect of deterioration. There are very few, if any, definite guidelines on the assessment of deterioration, and it is thus left to the judgment of the individual inspectors. In 1980, the Organization for Economic Cooperation and Development (OECD) issued a state-of-the-art review on the "Evaluation of the Load Carrying Capacity of Existing Road Bridges" (*108*). The report stated that the load-carrying capacity of existing bridges should be based on the actual condition of the structure and that the assessment of the bridges' strength should take into account such items as: (1) actual strength of materials, minimum sectional areas of structural members and location of reinforcement, and the type and state of corrosion, especially of structural steel reinforcement or prestressing tendons; (2) cracking, spalling, lamination of concrete, distortion, or yielding of structural steel; (3) loss of composite actions through debonding between components; (4) settlement, deformation or rotation producing redistribution of stresses or instability, and redistribution of permanent stresses due to prestressing, creep, shrinkage, and dead load; (5) restraints at joints and bearings, and the effectiveness of bolted joints; (6) the remaining life expectancy and condition of any fatigue prone details.

A very subjective area in the assessment of the strength of bridges is the case of deteriorated concrete. The limit states are more difficult to determine because traditional theories about structural behavior may no longer be valid. For example, in the case of flexure in a heavily deteriorated beam, the capacity of a section may be controlled by anchorage of the reinforcing steel rather than by the yield strength of the steel (*74*). The final report of NCHRP Project 10-15 "Strength Evaluation of Existing Reinforced Concrete Bridges" (*74*) also stated that for deterioration to affect the structural capacity of reinforced concrete bridges, deterioration must result in one or more of the following:

1. Loss of material from a critically stressed steel or concrete area.
2. Reduction of ultimate stress levels due to a change in the material properties.
3. Loss of structural continuity (composite action).
4. Loss of material, resulting in stress concentration (pitting of the reinforcing steel).
5. Nonuniform loss of material, resulting in a redistribution of the load due to relative stiffness changes.
6. Loss of material, resulting in a loss of stability.

It is generally held that deteriorated concrete bridges should be weaker than sound concrete bridges. However, tests have shown that this fact may not always be true. The following test reports have indicated that bridges in a moderate to advanced state of deterioration possess strength in excess of what they are given credit for. "In 1978 New York State initiated a research program to develop a low-cost field test method for the evaluation of structural strength. This effort was abandoned, when at the load levels attainable, it was shown that bridges with sound and deteriorated concrete in the tension zone did not differ in behavior" (*27*).

In a study by Oshiro and Hamada (*108A*), two reinforced concrete highway bridges, the Yaka and the Nakama, constructed in 1945 and 1955 respectively, were tested to determine the structural performance of these bridges. Field observations indicated the development of surface spalls and hollow areas as a result of expansive pressures caused by corrosion of main reinforcing bars. The surfaces of these bridges were in poor condition where progressive deterioration due to cracks and spalls was observed. A static field test was done by placing one or two trucks on each bridge to cause maximum positive moment at midspan. From the observation of lateral load distribution test results, it was concluded that the Guyon-Massonnet method is applicable in evaluation for elastic behavior of deteriorated bridges, unless the slab is seriously deteriorated. An ultimate bending test was also done on isolated beams taken from the two bridges. Test results showed that the rigidity of a beam that is part of an existing bridge is much higher than that expected from an isolated beam and that the effects of deterioration on main beams vary. Even though the bridges were highly deteriorated in appearance, the ultimate strength of test beams was higher than that computed by the ACI code, indicating no significant losses of strength.

Several of the bridge tests conducted by the Ontario Ministry of Transportation and Communications have also indicated the capability of deteriorated bridges to carry high loads in spite of their deteriorated conditions. Several examples are cited here.

The Tansley Bridge had a concrete deck slab that was in an advanced state of deterioration at the time of testing (*14*). Test results showed that the deck had undergone progressive deterioration for 5 years. The test also showed that the bridge deck could sustain high concentrated loads in spite of its deteriorated condition. The bridge was calculated to have a higher flexural stiffness than it was thought to possess.

The CPR Overhead Bridge was built in 1925 (*14*). At the time of testing, the bridge showed signs of considerable deterioration with exposed steel on the outer edges of the deck and considerable spalling on the underside of the deck. Because of the condition of the bridge, its load-carrying capacity was difficult to assess by analytical means; therefore, a decision was made to load test the bridge. The test demonstrated that in spite of its advanced state of deterioration, the bridge possessed better distributional properties than those predicted by AASHTO coefficients.

The Coniston Creek Bridge was reported to be in an advanced state of deterioration at the time of testing (*14*). The structure was tested to establish the true load carrying capacity of the bridge and also to study the behavior of such a structure. The test confirmed that in spite of its advanced state of deterioration, the bridge could still safely carry modern day traffic.

The New York State Department of Transportation tested a 52-year-old reinforced concrete T-beam bridge to failure to evaluate the effects of concrete deterioration on load capacity (*21*). The condition of the bridge was rated 2.5 on a scale from 1 (potentially hazardous) to 7 (new condition). The concrete deck was highly fractured throughout and the cement paste severely deteriorated locally. Tension reinforcing bars exposed by spalled concrete had lost from 1 to 2 percent of their cross-sectional area. Site conditions did not permit the structure to be tested as a single unit, and loading was done on single and double-T test specimens. The author drew the conclusion that the deterioration noted had no significance with respect to load-carrying capacity of this bridge. A further conclusion was drawn that deterioration sufficient for substantial reduction of the capacity of a structure would be manifested in a local collapse, and that overall failure need not be a concern.

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