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Advanced Analysis and Testing Methods for Concrete Bridge Evaluation and Design

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Editors:
Benjamin Z. Dymond and Bruno Massicotte

American Concrete Institute
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Advanced Analysis and Testing Methods for Concrete Bridge Evaluation and Design

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The cover photo depicting testing of a reinforced concrete bridge to failure was courtesy of co-editor Bruno Massicotte.

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PREFACE

Advanced Analysis and Testing Methods for Concrete Bridge Evaluation and Design

In recent years, both researchers and practicing engineers worldwide have been refining state-of-the-art and emerging technologies for the strength evaluation and design of concrete bridges using advanced computational analysis and load testing methods. Papers discussing the implementation of the following topics were considered for inclusion in this Special Publication: advanced nonlinear modeling and nonlinear finite element analysis (NLFEA), structural versus element rating, determination of structure specific reliability indices, load testing beyond the service level, load testing to failure, and use of continuous monitoring for detecting anomalies. To exchange international experiences among a global group of researchers, ACI Committees 342 and 343 organized two sessions entitled "Advanced Analysis and Testing Methods for Concrete Bridge Evaluation and Design" at the Spring 2019 ACI Convention in Québec City, Québec, Canada. This Special Publication contains the technical papers from experts who presented their work at these sessions. The first session was focused on field and laboratory testing and the second session was focused on analytical work and nonlinear finite element modeling. The technical papers in this Special Publication are organized in the order in which they were presented at the ACI Convention.

Overall, in this Special Publication, authors from different backgrounds and geographical locations share their experiences and perspectives on the strength evaluation and design of concrete bridges using advanced computational analysis and load testing methods. Contributions were made from different regions of the world, including Canada, Italy, and the United States, and the technical papers were authored by experts at universities, government agencies, and private companies. The technical papers considered both advanced computational analysis and load testing methods for the strength evaluation and design of concrete bridges.

The co-editors, Dr. Benjamin Dymond and Dr. Bruno Massicotte, are grateful for the contributions from the Special Publication authors and sincerely value the time and effort of the authors in preparing the papers in this volume. Furthermore, the Special Publication would not have been possible without the effort expended by the 24 experts who peer reviewed the papers in this volume.

Co-Editors

Benjamin Dymond and
Bruno Massicotte

TABLE OF CONTENTS

Inelastic Shear Distribution in Prestressed Concrete Girder Bridges

Benjamin Z. Dymond, Catherine E. W. French, Carol K. Shield

Synopsis: An experimental investigation was conducted on a full-scale prestressed concrete girder laboratory bridge to determine whether linear elastic shear distribution principles are conservative for load rating at ultimate capacity. A secondary goal was to determine whether existing web-shear cracks would be visible in an unloaded state. Two tests were conducted to failure (one near the end with a partial-depth diaphragm and one near the end without) to determine if the most loaded interior girder shed shear force to adjacent girders as it transitioned from uncracked to cracked to failure. Failure during each test was characterized by web-shear crushing and bridge deck punching at the peak applied load. Differences in the behavior of the two ends (with and without partial depth end diaphragm) affected the diagonal crack pattern, shear distribution, and loads at cracking and failure. The effect on loading was less than 10%. Inelastic shear distribution results indicated the girder carrying the most load redistributed shear to the other girders as it lost stiffness due to cracking. Use of linear elastic load distribution factors was conservative considering shear distribution at ultimate capacity. The visibility of web-shear cracks in an unloaded state was found to be a function of stirrup spacing.

Keywords: shear distribution, inelastic behavior, failure, concrete bridge, load testing, prestressed concrete

MOTIVATION AND BACKGROUND

Highway bridge owners regularly assign load ratings to bridge girders, which reflect the capacity of the component to carry traffic. Establishing girder load ratings requires an estimate of the member capacity (along with the amount of deterioration over time) and the live load demand. The capacity is calculated considering ultimate behavior and multiplied by a resistance factor (e.g., ϕV_n). The live load demand on an individual girder is estimated with distribution factors, which are typically derived based on linear elastic analysis and approximate how the traffic load distributes through the bridge system to an individual girder.

Engineers typically rely on the American Association of State Highway Transportation Officials (AASHTO) Specifications to assign load ratings and evaluate shear behavior. However, AASHTO requirements for shear have changed significantly over the years. As a result, some prestressed concrete girder bridges designed with previous AASHTO standards rate poorly for shear using current AASHTO standards, despite the fact that the girders may show no signs of distress under normal traffic loading conditions. Thus, the girders are often deemed to be in good condition, and therefore, the resulting shear rating may be neglected as outlined in Section 6A.5.8 of the AASHTO Manual for Bridge Evaluation (MBE) (2011), which states that "in-service concrete bridges that show no visible signs of shear distress need not be checked for shear when rating for the design load or legal loads."

The primary goal of this research was to experimentally determine if an interior bridge girder shed shear force to adjacent girders as that beam transitioned from uncracked to cracked to failure. If shear force redistributed in the inelastic range of behavior after cracking and before failure, an inherent factor of safety may exist and use of linear elastic load distribution factors may be conservative when considering shear distribution at ultimate capacity. A secondary goal was to determine if initial web-shear cracking was visible in an unloaded state.

Load Rating with Elastic and Inelastic Principles

The methodology behind evaluation of existing bridges is transitioning from load factor rating (LFR), which aligned with the AASHTO Standard Specifications, to load and resistance factor rating (LRFR), which aligns with the AASHTO LRFD Specifications. While there are several differences between the rating factor (RF) equations for LFR and LRFR (e.g., nomenclature changes, separation of dead load by type), the general structure of the equation remains the same and is shown in Eqn. 1.

$$\text{Shear RF} = \frac{\text{(Resistance Factor)*(Shear Capacity) - (Load Factor)*(Dead Load)}}{\text{(Load Factor)*(Live Load Shear Demand)*(Impact Factor)}} \quad (1)$$

There is one key assumption present in both LFR and LRFR methodologies that is subtle and embedded in the calculation of the capacity and the live load. Calculation of a shear rating factor requires knowledge of the shear capacity at the *ultimate limit state* and knowledge of the live load shear demand on an individual girder estimated with distribution factors based on *linear elastic* analysis. Use of ultimate shear capacity and elastic distribution factors in load rating mixes principles related to elastic versus inelastic structural behavior.

Elastic and Inelastic Shear Distribution

The first load distribution principles for concrete slabs and beams published in the AASHTO Standard Specifications (1931) were developed by Westergaard (1930), confirmed by Newmark et al. (1946), and were based on elastic plate theory. The AASHTO Standard Specifications (2002) required use of the lever rule or "*S*-over" equations to calculate shear distribution factors. The lever rule assumes that the bridge deck is simply supported (hinged) over the interior girders in any cross section. At exterior girders, it is assumed that the deck panel is continuous with the overhang, which simulates a propped cantilever. These assumptions make the deck cross section statically determinate and the support reactions (i.e., distribution of shear among girders) can be readily calculated. The "*S*-over" equations were expressed in an S/D format, where S is the girder spacing in feet and D is a constant value for prestressed concrete girders of 7.0 and 5.5 for one lane loaded and two lanes loaded, respectively. Equations developed by Zokaie et al. (1991a; 1991b) are used for shear distribution factors in the AASHTO LRFD Specifications (2017). These equations are dependent on the girder spacing and were developed using linear elastic frame and shell finite element models loaded with the HS20 truck. The LRFD equations were calibrated against a database of constructed bridges to verify their applicability and generally produced results within five percent of those from a detailed finite-element analysis (Zokaie, 1991b).