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Advanced Analysis and Testing Methods for Concrete Bridge Evaluation and Design

Editors:
Benjamin Z. Dymond and Bruno Massicotte

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American Concrete Institute
Always advancing

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 242 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

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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

Monitoring and Assessment of a Prestressed Concrete Segmental Box Girder Bridge

Marc Savard and Jean-François Laflamme

Synopsis: Several of the first prestressed concrete segmental bridges in North America were built in Quebec, Canada. The Rivière-aux-Mulets bridge was one of them. Built in the early 1960s, this bridge experienced several disorders due to inadequate design criteria enforced at that time. Despite a structural strengthening in the late 1980s, a bridge behavior follow-up has been required to ensure reliability. The structural health monitoring program implemented to track structural disorders, along with results from modal analysis and diagnostic load tests, is presented with a focus on the instrumentation and the data analysis. A three-dimensional finite element model was developed and calibrated using the frequencies and mode shapes detected under ambient traffic conditions. Data analyses showed that the expansion bearings were frozen, causing bending of the associated piers, which generated axial forces in the deck and decompression of concrete in the area surrounding active cracks. This process enables premature failure of prestressing tendons in the vicinity of these cracks, especially those located in the top flange, which is a corrosion-friendly environment. Development of cracks and associated prestress loss caused a reduction in the bridge load-carrying capacity. Analyses of health monitoring data led to acute assessment of the overall bridge structural performance.

Keywords: data analysis, finite element analysis, load tests, modal analysis, prestressed concrete bridge, structural damage, structural health monitoring

Field Testing to Failure of a Skewed Solid Concrete Slab Bridge

Fabien Lagier, Bruno Massicotte, David Conciatori, Jean-François Laflamme

Synopsis: In 2006 in Quebec, a skewed cantilever solid concrete slab bridge without shear reinforcement collapsed due to a shear failure, which highlighted the need to improve the assessment of this type of structure. A large experimental program was carried out to test three decommissioned solid slab bridges to failure. In parallel, an extensive nonlinear finite element analysis study was performed with the aim of better understanding the failure mechanisms, the degree of load redistribution, and to gain insight into the ultimate shear capacity of these structures. A beam shear failure mode was expected for the first two bridge tests, but a flexural failure mode was observed. This paper focusses mainly on the last field test of a simply supported solid slab bridge having a 40 degree skew. The load position and the loading protocol were established with the objective of causing a shear failure at the obtuse corner of the slab where high shear forces develop. The main test motivation was to illustrate that simply supported solid slab bridges would normally not be prone to shear failure due to an intrinsic redundancy. The paper presents experimental techniques that could help bridge owners in assessing the performance of their bridges. The test results also provide valuable information for calibrating nonlinear element models that can be used for assessing the carrying capacity of existing concrete bridges.

Although the actual bridge conditions were worse than anticipated, a global shear failure mode occurred near the obtuse corner at a maximum load of 1400 kN, which significantly exceeded the factored shear force due to the maximum traffic load. The failure was followed by a gradual load redistribution toward undamaged portions of the slab. This field test confirmed the assumption of non-fragility for this type of bridge, where support conditions enable development of an intrinsic redundancy. Despite these observations, nonlinear analyses carried out in parallel to the testing program indicated that this beneficial effect diminishes with an increase of slab thickness.

Keywords: solid slab bridges, field testing, load rating, shear failure, nonlinear finite element analysis

Instrumentation, Monitoring and Load Testing of the Champlain Bridge

Dominic Lavigne

Synopsis: This paper presents the methods used by Jacques Cartier and Champlain Bridges Incorporated (JCCBI) to monitor the Champlain Bridge in its maintenance and structural monitoring program. The monitoring program, which was established in 2012 and increased in scope over time to obtain a clearer picture of the state and behavior of the Champlain Bridge, allows continual monitoring of the structural behavior of the bridge by monitoring critical members flexural response. Established key performance indicators detectable by the equipment are used to alert JCCBI to react quickly to ensure the structural integrity of the bridge. This paper describes the instrumentation and monitoring of the edge girders of 50 concrete spans and 45 pier caps of the Champlain Bridge, using optical sensors for recording strains on these elements. Over 330 optical sensors were installed on the bridge to record data continuously at 50 Hz. Such data contains invaluable information for monitoring the bridge response and can provide early warnings to indicate structural degradation. Through these means, amongst others, JCCBI preventively manages the risks associated with this vital infrastructure reaching the end of its service life.

Keywords: Champlain Bridge, concrete bridge, JCCBI, monitoring, optical strain sensors, structural health monitoring, SHM

Load Rating Reinforced Concrete Bridges without Plans: State-of-the-Practice

Rémy D. Lequesne and William N. Collins

Synopsis: In response to Federal Highway Administration requirements, several states are in the process of ensuring all bridges within their inventories are load rated. A challenging aspect of this effort is load rating reinforced concrete bridges that have no structural plans when there are thousands of such structures within a state inventory. To inform these efforts, the literature was reviewed to identify existing methodologies and a survey was distributed to engineers at state departments of transportation throughout the United States to understand how practicing engineers approach this problem. The survey responses show there are numerous bridges in the U.S. without plans; over 20,000 bridges without plans are located in the 18 states that provided responses. Concrete structures comprise 70% of such bridges. To load rate concrete bridges without plans, most responding states report primarily using engineering judgement, which may include reference to performance under existing traffic, era-specific design traffic loads, assumed material properties and reinforcement quantities, or data collected using load tests or non-destructive evaluation. Several methodologies are described and advantages/limitations of each are discussed.

Keywords: load rating, concrete, bridge, bridge with unknown details, NDE

Estimation of Steel Rebar Strength in Existing Concrete Bridges

Alessandro P. Fantilli and Bernardino Chiaia

Synopsis: To design a retrofit and/or maintenance protocol for existing reinforced concrete bridges, the assessment of rebar steel strength is generally required. The current methodology consists of uniaxial tensile tests performed on bar segments extracted from a structural element. Nevertheless, in several situations (e.g., the assessment of bridges in service), this traditional method cannot be used. Hence, a new simplified approach is introduced herein. It consists of the so-called "strength-for-age curves," which relate the average strength of steel to the year of construction. Such curves are statistically computed from a database stored in the Department of Structural and Geotechnical Engineering of Politecnico di Torino (Italy). As a result, the yield and tensile strength values experimentally measured from rebar in two existing bridges in Northern Italy, built in 1930 and 1975, respectively, were correctly predicted using the proposed model.

Keywords: reinforced concrete, existing bridges, tensile strength, yield strength, steel reinforcing bar, strength-for-age curves, uniaxial tensile test

Seismic Performance of Unreinforced Concrete Railroad Bridge Piers

Qiang Gui and Zhongguo John Ma

Synopsis: Research on the seismic performance of unreinforced concrete railroad bridge substructures is presented. The restraining effect of a continuous rail track structure, which is considered to contribute to better seismic performance of railroad bridges compared with highway bridges, was investigated. A numerical modelling scheme that takes into consideration the nonlinear properties of the ballast and bearings as well as steel and concrete materials was proposed and validated using previous full-scale field testing. The equivalent spring stiffness of the rail track system was obtained and used in the subsequent small-scale shaking table experiment, which investigated the dynamic response of column-shaped rigid body specimens with a spring restraint on the top. Several parameters were considered in the test matrix such as the stiffness of the restraint spring, the height/breadth ratio, the ground excitation, and single-body or multi-body configurations. Discussion regarding the testing results are also presented.

Keywords: continuous rail track, nonlinear link element, railroad bridge, restraining effect, seismic performance, shaking table, video analysis

Evaluation of the Orientation of Concrete Finishing Machines in Skewed Bridges

Faress Hraib, Li Hui, Brandon Gillis, Miguel Vicente, and Riyadh Hindi

Synopsis: During bridge construction, the concrete finishing machine weight, along with other dead and live loads, affects the stability of the structure during construction and the service life of the bridge. These eccentric unbalanced loads lead to torsional moments in the exterior girders of the bridge, deflection of the overhang, and excessive rotations in the exterior girders. In skewed bridges, the finishing (screed) machine can be oriented parallel to the skew or perpendicular to the girders during construction. This study focused on evaluating different orientations of the machine along the span of skewed bridges. Finite element models of bridges with different skew angles were developed using SAP2000 to simulate construction conditions. These bridge models were then subjected to different machine orientations to form a better understanding of this phenomenon and to find the most effective method to operate the concrete finishing machines. The results showed that moving the screed machine parallel to the skew angle led to rotations that were more balanced between the exterior girders compared to moving it perpendicular to the girders. Therefore, a more leveled concrete surface can be obtained when running the machine parallel to the skew.

Keywords: composite girder bridges, deck slab construction, screed machine orientation, skewed bridges, bridge construction loads

Non-Linear Evaluation of Strengthening Techniques for the Champlain Bridge

Denis Mitchell, Bruno Massicotte, William D. Cook, and Emre Yildiz

Synopsis: The existing Champlain Bridge is a major structure in Montreal. It contains 50 concrete spans. The 10 ft (3.1 m) deep I-girders span 172 ft (52.4 m) and are post-tensioned. Because the prestressing steel has suffered from corrosion, it was necessary to use advanced techniques to evaluate the performance of these I-girders. Detailed two-dimensional non-linear finite element modelling was used to determine the responses at service load and at ultimate. Three-dimensional finite element modelling was carried out to determine the loading for the two-dimensional modelling. The serviceability checks examined if cracking would occur and the strength requirements were evaluated using predicted demand-to-capacity ratios (D/C). These analysis tools also enabled the influence of a number of strengthening techniques to be assessed. The influence of different strengthening techniques on the predicted responses of the diaphragms was also studied. The combinations of strengthening measures were found to be effective in achieving the desired serviceability and strength requirements.

Keywords: bridges, post-tensioned concrete, deterioration, flexure, shear, finite element analysis, CFRP, girders, rehabilitation

Numerical Modeling Methodology for Strength Evaluation of Deep Bridge Bent Caps

Anish Sharma and Serhan Guner

Synopsis: Due to the increase in traffic and transported freight in the past decades, a significant number of in-service bridges have been subjected to loads above their original design capacities. Bridge structures typically incorporate deep concrete elements, such as cap beams or bent caps, with higher shear strengths than slender elements. However, many in-service bridges did not account for the deep beam effects in their original design due to the lack of suitable analysis methods at that time. Nonlinear finite element analysis (NLFEA) can provide a better assessment of the load capacity of deep bridge bent beams while accounting for the deep beam action. However, there is little guidance on how to conduct a numerical strength evaluation using the NLFEA. This study presents a nonlinear modeling methodology for the strength evaluation of deep bridge bents while considering advanced concrete behavior such as tension stiffening, compression softening, and dowel action. Five existing bridge bent beams are examined using the proposed methodology. The effectiveness and advantages of the proposed methodology are discussed by comparing the numerical results, including the load-displacement responses, load capacities, cracking patterns and failure modes, with the strut-and-tie and sectional analysis methods. Important modeling considerations are also discussed to assist practitioners in accurately evaluating deep bridge bents.

Keywords: bridge bent beams, deep beams, NLFEA, strength evaluation, safety assessment, failure, sectional method, strut-and-tie method, rehabilitation

Seismic Simulation of Bridges Considering Bending and Torsion Interaction

Yang Yang and Ruili He

Synopsis: Concrete columns in curved bridges have reportedly showed high interaction between bending and torsional moments when subjected to design-level earthquake loading. In order to accurately evaluate the performance of curved bridges under earthquake loadings, it is necessary to incorporate the interaction behavior into computational models. However, very limited work has been reported in the literature, which includes finite element models involving three-dimensional solid elements and user-developed fiber elements in open-source computing tools; the former involves significant computational effort when multiple levels of earthquake records need to be considered, while the latter is not widely available in analysis tools like OpenSees. This study developed a modeling technique to simulate the interaction between bending and torsional moments in bridge columns through the discretization of the column into longitudinal, transverse, and diagonal elements. In this study, the developed modeling technique was validated against experimental data from a previous study, and case studies on typical curved bridges were presented to show its efficiency in seismic simulation.

Keywords: reinforced concrete, bridge column, cyclic loading, failure analysis, torsion, truss modeling