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Advances in Concrete Bridges: Design, Construction, Evaluation, and Rehabilitation

Editors:
Hail J. Kim, John J. Myers, and Antonio Nanni

SP-333

American Concrete Institute
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PREFACE

Advances in Concrete Bridges: Design, Construction, Evaluation, and Rehabilitation

Concrete bridges play an important role in the efficiency and reliability of transportation civil infrastructure. Significant advancements have been made over the last decades to enhance the performance and durability of bridge elements at affordable costs. From an application perspective, novel analysis techniques and construction methods are particularly notable, which have led to the realization of more sustainable built-environments. As far as the evaluation and rehabilitation of constructed bridges are concerned, new nondestructive testing approaches provide accurate diagnostics and advanced composites, such as carbon fiber reinforced polymer (CFRP), have become an alternative to conventional materials. This Special Publication (SP) contains nine papers selected from two technical sessions held at The ACI Concrete Convention and Exposition – Spring 2018, in Salt Lake City, UT. The objective of the SP is to present technical contributions aimed to understand the state of the art of concrete bridges, identify and discuss challenges, and suggest effective solutions for both practitioners and government engineers. All manuscripts were reviewed in accordance with the ACI publication policy. The Editors wish to thank all contributing authors and reviewers for their rigorous efforts. The Editors also gratefully acknowledge Ms. Barbara Coleman at ACI for her knowledgeable guidance in the development of the SP.

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A Numerical Analysis Methodology for the Strengthening of Deep Cap Beams

Rafael A. Salgado, Serhan Guner

Synopsis: A significant number of in-service bridges have been subjected to loads above their original design capacities due to the increase in traffic and transported freight in the past decades. Externally bonded fiber reinforced polymers (FRP) is a non-destructive retrofit technique that has become common for the strengthening of overloaded cap beams of bridges. However, there is a lack of analysis methods for the retrofitted cap beams that can accurately predict the retrofitted structural response while accounting for the critical material behaviors such as bond-slip relationships, confinement effects, and redistribution of stresses. In this study, an analysis methodology using nonlinear finite element models is proposed for cap beams retrofitted with externally bonded FRP fabrics. A two-stage verification of the proposed methodology was employed: a constitutive modeling and critical behavior of materials verification using experimental results available in the literature; and a system-level load capacity determination using a large, in-situ structure. The proposed methodology was able to capture the FRP-concrete composite structural behavior and the experimentally observed failure modes. The FRP retrofit layout created using the results of this study increased the capacity of the initially overloaded cap beam in 27%, granting it a 6% extra capacity under its ultimate loading condition.

Keywords*:* deep beams; nonlinear analysis; cap beam; structural assessment; FRP; retrofit; analysis methodology

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Surrogate Modeling for Self-Consolidating Concrete Characteristics Estimation for Efficient Prestressed Bridge Construction

Junwon Seo and Jharna Pokhrel

Synopsis: This paper investigates the effects of material constituents on fresh and hardened properties of Self-Consolidating Concrete (SCC) mixture necessary for efficient prestressed bridge girder fabrication using a surrogate modeling technique. Response surface methodology (RSM)-based surrogate models consisting of input parameters such as density of coarse and fine aggregate were created based upon the past laboratory testing results for different SCC mixture trials. These models were used to estimate various SCC material characteristics, including slump flow, J-ring flow, passing ability, filling capacity, Visual Stability Index (VSI), T_{50} concrete spread time to reach the 50.8 cm [20 in] mark), column segregation, 16-hour compressive strength, and 28-days compressive strength, while examining the correlation between the input parameters on each material characteristic. To observe the effect of core input parameters in an efficient manner, 2D contour plot and 3D surface plot for material characteristics were also created. Then, statistical analyses with the testing results were performed to determine the accuracy of the surrogate models in terms of coefficient of regression (R^2). Most of the R^2 values are higher than 90%, indicating a higher degree of correlation among the testing and surrogate data. Average predicted-to-measure ratios of the surrogate models were almost equal to or slightly greater than 1.00, showing good agreement with the testing results, and specifically the surrogate and testing values for J-ring flow and 28-days compressive strength were nearly identical. Key findings indicate that the coarse aggregate content significantly affected the characteristics of the SCC mixtures.

Keywords: bridge; characteristics; girder; material; prestressed; SCC; surrogate modeling

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On the Application of Basalt-Fiber Reinforced Polymer (BFRP) Bars to Prestressed Slab Elements Typical of the Precast Concrete Industry

Bruno Dal Lago, Davide Bisi and Liberato Ferrara

Synopsis: Basalt-Fiber Reinforced Polymer (BFRP) bars have been recently proposed to be used to prestress precast concrete elements. Mechanical properties, potential low production cost, low carbon footprint, and enhanced durability make the application of BFRP to prestressed concrete promising. Nevertheless, some issues related to anchorage and sustained stress still need to be fully addressed. Applications are so far limited to few laboratory tests. This paper discusses how the Serviceability Limit State (SLS) and Ultimate Limit State (ULS) checks of pre-stressed elements employing this technology vary with respect to elements pre-stressed with steel tendons. Furthermore, an attempt is made to investigate the potential application in the precast concrete industry, by analyzing several typical roof and floor slab elements with different cross-section. This investigation highlights which type of element could be more advantageously switched to the use of pre-stressed BFRP bars, and at which cost in terms of structural performance.

Keywords: basalt; creep; losses; nonlinear analysis; prestressing; serviceability; slab elements; structural design

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Monitoring and Rehabilitation of Damaged Bridge Beam of Middle Ring Road in Shanghai

Huayong Wu, Rongxin Zhao, and Yun Xing

Synopsis: In the morning of 23rd May of 2016, a traffic accident happened in the Middle Ring Road between the ramps of Zhenhua Road and Wanrong Road Shanghai, China. A series on-spot tests are carried out and a real time wireless sensor system is deployed in the bridge. The beam state is reasonably estimated according to the monitoring measurements and the rehabilitation is carried out through 28 steps. Health monitoring measurements show that the beam inclination is below 0.2°, and the beam stays in a stable state after traffic is resumed, which indicates that the repair has met the expected requirements..

Keywords: beam inclination; bridge; monitoring; rehabilitation

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Seismic Experiments and Analysis of Repaired Bridge Columns Using CFRP Donut

Ruo-Yang Wu and Chris P. Pantelides

Synopsis: Two severely damaged concrete column-to-cap beam specimens were successfully repaired, using a carbon fiber-reinforced polymer (CFRP) cylindrical shell, non-shrink repair concrete, and headed steel bars. The first cast-in-place specimen experienced concrete crushing and longitudinal bars fracture/buckling; for the second precast specimen, the column was completely separated from the cap beam. In this paper, two analytical models, Model Fiber and Model Rotational Spring (RS), simulating the seismic performance of the repaired specimens are proposed. In Model Fiber, plasticity considering bond-slip effects was distributed over the defined plastic hinge length of the nonlinear beam-column element. In Model RS, a non-linear rotational spring was used to consider the concentrated plasticity located at the repaired cross-section. Low-cycle fatigue of the damaged column longitudinal steel bars was included in the analytical models. Simulations show that the analytical results, in terms of hysteretic response and moment-rotation, are in very good agreement with the experimental results. Model Fiber performed better for predicting the pinching effect in the hysteretic response of the repaired cast-in-place specimen; Model RS performed better for matching the hysteresis curves of the repaired precast concrete specimen. In addition, Model Fiber was able to predict the local response of the columns including the fracture of longitudinal bars due to low-cycle fatigue.

Keywords: analytical model; bond slip; damage; experiments, fiber reinforced polymer composites; low-cycle fatigue; plastic hinge relocation; repair; seismic

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Pedestrian Bridge as Clarifying Example of FRP-RC/PC Design

Marco Rossini, Saverio Spadea, Antonio Nanni

Synopsis: Employment of corrosion-resistant reinforcement represents a widely-recognized effective strategy to ensure long-term durability of reinforced concrete (RC) and prestressed concrete (PC) structures. Fiber-reinforced polymer (FRP) composites have proved to be a reliable non-metallic solution, able to ensure both the required mechanical performance and corrosion resistance. FRP-RC infrastructural applications are currently spreading; conversely, FRP-PC bridges are still considered state of the art prototypes. Many are the conceptual and practical challenges accompanying this innovative technology: brittleness of FRP reinforcement, likelihood of tension-controlled failure, limitations on the initial pull force, limitations on the sustained load that the member can carry, and service requirements that may control the design. Reports published by ACI committee 440 do not yet address FRP-RC/PC provisions in a consistent way. Discrepancies exist on how ACI 440.1R and ACI 440.4R approach FRP-RC/PC design, having the latter not being updated since the first generation of FRP regulations. This paper deals with the philosophy behind the design of the precast Carbon FRP-PC/Basalt FRP-RC double-tee girders and the auxiliary Basalt FRP-RC/Glass FRP-RC members that constitute the structure of a recently built pedestrian bridge. This study is an attempt to address the challenges still preventing the wide acceptance of CFRP in prestress applications and to unify the design approach for FRP-RC/PC structures. This successful case-study validates the proposed rationale and supports a slight relaxation of the design limits in terms of initial pull force.

Keywords: basalt FRP; carbon FRP; design; glass FRP; jacking stress; prestressed concrete; standards

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Shear Tests on Prestressed Concrete Continuous Beams

Martin Herbrand, Viviane Adam, Josef Hegger

Synopsis: Due to increased traffic loads and changes in the code provisions many highway bridges in Germany exhibit deficits in shear capacity according to current codes. The majority of these bridges' structures comprises continuous concrete beams whose calculatory shear capacity is often exceeded by now. However, the actual shear capacity of prestressed concrete continuous beams is usually underestimated since the design procedures have been derived on the basis of single span beam tests and neglect significant shear transfer mechanisms. In order to extend the service life of existing bridges, the reserves in the design procedures can be partially taken advantage of by the application of refined design approaches. For this reason, five shear tests on prestressed concrete continuous beams have been performed at the Institute of Structural Concrete of RWTH Aachen University in Germany. Within these tests, the influence of cross-section type (rectangular and I-shaped cross-section), load distribution (concentrated and distributed loads) and the shear reinforcement ratio is investigated. In this paper, the test results of three beams under concentrated loads will be presented.

Keywords: concrete; continuous beams; distributed loads; post-tensioning; shear

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Concrete Beams with Fully Corroded Steel Repaired with CFRP Laminates

Needa Lingga, Yasir Saeed, Anas Yosefani, and Franz Rad

Synopsis: This research focused on concrete beams with voids simulating beams with fully corroded steel that were repaired with CFRP laminates. The experimental program included testing five, approximately one- third-scaled simply supported rectangular concrete beams. In three beams, the oiled steel rebars for flexure and shear were safely pulled out of the formwork after the concrete had cured for six hours, leaving voids. This technique was used to represent an extreme case of corrosion, albeit non-realistic, that is even worse than being exposed to the most corrosive environment. The aim was to investigate the extent of improvement by CFRP to flexural and shear capacity of beams that contain fully corroded steel bars, simulated by voids. The first specimen was with voids representing completely deteriorated steel. The second was a plain concrete beam without voids. The third beam was a typical code-designed reinforced concrete (RC) beam, that represented the "original undeteriorated" beam. The two remaining deteriorated beams were repaired by externally bonding one and two layers of CFRP. Load carrying capacity, deflection, and ductility were measured and compared. The novel results of this investigation were that test results showed that one layer of CFRP increased the load capacity to slightly higher than the RC beam, and two layers of CFRP increased it by a factor of two. Finally, a computer model was created to estimate the performance of the tested beams and to carry out a parametric study to investigate the effects of CFRP longitudinal reinforcement ratio and CFRP transverse confinement ratio on the flexural performance of CFRP-repaired concrete beams. The predicted contribution of CFRP to flexure and shear capacities was in good agreement with test results.

Keywords: beam; carbon fiber reinforced polymer; CFRP; concrete; corrosion; flexure; retrofitting

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Rational Fuzzy Logic Condition Rating Model of Reinforced Concrete Bridge Decks Using Non-destructive Testing and Visual Inspection

Tarek Omar and Moncef L. Nehdi

Synopsis: Bridge deck condition rating systems commonly use measurements of obvious defects recorded through visual investigation. Accordingly, the condition of bridge decks is rated linguistically with inherent vagueness in the description of the deck condition. Although several advanced non-destructive testing (NDT) technologies have emerged for inspecting bridge decks, their results have yet to be incorporated in the condition rating process. The present study establishes a unique link between NDT technologies and inspector findings by developing a novel bridge deck condition rating index (BDCI). The proposed procedure captures the integrated results of infrared thermography (IRT) and ground penetrating radar (GPR), along with visual inspection judgement deployed to evaluate a full-scale ageing concrete bridge deck. The information sought to identify the parameters affecting the integration process was gathered from bridge engineers with extensive experience and intuition. The analysis process utilized the fuzzy set theory, thus overcoming the inherent scientific uncertainties and imprecision in the measurements of bridge deck subsurface defects by IRT and GPR testing along with surface defects identified through bridge inspector observations. Integrating the proposed BDCI procedure with existing bridge management systems can provide a detailed and reliable appraisal of bridge health, thus helping transportation agencies in optimizing budgets and prioritizing maintenance, repair, and rehabilitation efforts.

Keywords: bridge deck, condition rating, fuzzy logic, ground penetrating radar, infrared thermography, uncertainty, visual inspection