The 16th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures

Co-Chairs:
A. M. Okeil
P. Sadeghian
J. J. Myers
M. D. Lopez

American Concrete Institute
Always advancing

NEx
An ACI Center of Excellence for Nonmetallic Building Materials

IIFC International Institute for FRP in Construction

MST BAR
MAXIMUM STRENGTH GFRP

FYFE

ACMA
American Composites Manufacturers Association
FRP Rebar Manufacturers Council

MCTI Missouri Center for Transportation Innovation

Missouri S&T

Simpson Strong-Tie

Modjeski and Masters

Preface

The 16th International Symposium on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures (FRPRCS-16) was organized by ACI Committee 440 (Fiber-Reinforced Polymer Reinforcement) and held on March 23 and 24, 2024, at the ACI Spring 2024 Convention in New Orleans, LA. FRPRCS-16 gathers researchers, practitioners, owners, and manufacturers from the United States and abroad, involved in the use of FRPs as reinforcement for concrete and masonry structures, both for new construction and for strengthening and rehabilitation of existing structures. FRPRCS is the longest running conference series on the application of FRP in civil construction, commencing in Vancouver, BC, in 1993. FRPRCS has been one of the two official conference series of the International Institute for FRP in Construction (IIFC) since 2018 (the other is the CICE series). These conference series rotate between Europe, Asia, and the Americas, with alternating years between CICE and FRPRCS. The ACI convention has previously cosponsored the FRPRCS symposium in Anaheim (2017), Tampa (2011), Kansas City (2005), and Baltimore (1999).

In addition to the collection of abstracts found at the end of this program, FRPRCS-16 produced a Special Publication containing a total of 52 peer-reviewed technical manuscripts from 20 different countries from around the world. Papers are organized in the following topics: (1) FRP Bond and Anchorage in Concrete Structures; (2) Strengthening of Concrete Structures using FRP Systems; (3) FRP Materials, Properties, Tests and Standards; (4) Emerging FRP Systems and Successful Project Applications; (5) FRP-Reinforced Concrete Structures; (6) Advances in FRP Applications in Masonry Structures; (7) Seismic Resistance of FRP-Reinforced/Strengthened Concrete Structures; (8) Behavior of Prestressed Concrete Structures; (9) FRP Use in column Applications; (10) Effect of Extreme Events on FRP-Reinforced/Strengthened Structures; (11) Durability of FRP Systems; and (12) Advanced Analysis of FRP Reinforced Concrete Structures.

The breadth and depth of the knowledge presented in these papers is clear evidence of the maturity of the field of composite materials in civil infrastructure. The ACI Committee 440 is witness to this evolution, with its first published ACI CODE-440.11, "Building Code Requirements for Structural Concrete with Glass Fiber Reinforced Polymer (CFRP) Bars," published in 2022. A second code document on fiber reinforced polymer for repair and rehabilitation of concrete is under development.

The publication of the sixteenth volume in the symposium series could not have occurred without the support and dedication of many individuals. The editors would like to recognize the authors who diligently submitted their original papers; the reviewers, many of them members of ACI Committee 440, who provided critical review and direction to improve these papers; ACI editorial staff who guided the publication process; and the support of the American Concrete Institute (ACI) and the International Institute for FRP in Construction (IIFC) during the many months of preparation for the Symposium.

FRPRCS-16 Co-chairs:

A. M. Okeil, Louisiana State University

J. J. Myers, Missouri S&T

P. Sadeghian, Dalhousie University

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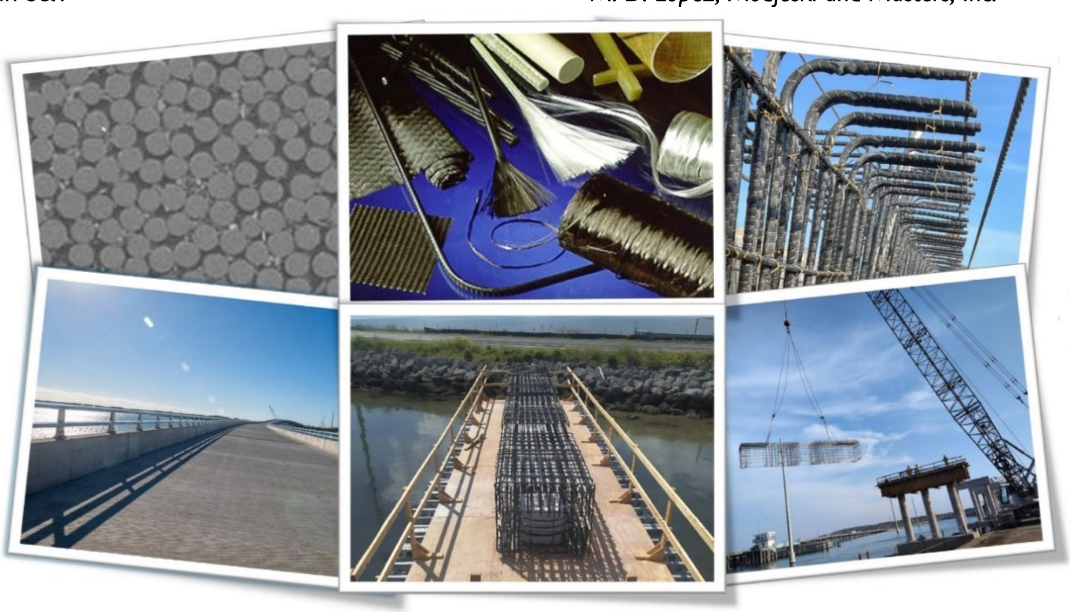

Program At A Glance

SATURDAY

8:00 a.m.–10:00 a.m.

Session 1: FRP Bond and Anchorage in Concrete Structures *Room: Strand 12B*	**Session 2: Strengthening of Concrete Structures Using FRP Systems** *Room: Strand 13B*

10:30 a.m.–12:30 p.m.

Session 3: FRP Materials: Properties, Tests and Standards *Room: Strand 12B*	**Session 4: Emerging FRP Systems and Successful Project Applications** *Room: Strand 13B*

1:00 p.m.–3:00 p.m.

Session 5: FRP-reinforced Concrete Structures *Room: Strand 12B*	**Session 6: FRP Design Codes and Guidelines** *Room: Strand 13B*

3:30 p.m.–5:30 p.m.

Session 7: Advances in FRP Applications in Masonry Structures *Room: Strand 12B*	**Session 8: Seismic Resistance of FRP-Reinforced/Strengthened Concrete Structures** *Room: Strand 13B*

6:30 p.m.–8:30 p.m.

FRPRCS-16 Reception and Student Poster Session

Room: Imperial 5

SUNDAY

8:00 a.m.–10:00 a.m.

Session 9: FRP Bond and Anchorage in Concrete Structures *Room: Strand 12B*	**Session 10: Behavior and Design of Prestressed Concrete Structures** *Room: Strand 13B*

10:30 a.m.–12:30 p.m.

Session 11: FRP Use in Column Applications *Room: Strand 12B*	**Session 12: Effects of Extreme Events on FRP-Reinforced/Strengthened Structures** *Room: Strand 13B*

1:00 p.m.–3:00 p.m.

Session 13: Durability of FRP Systems *Room: Strand 12B*	**Session 14: Advanced Analysis of FRP Reinforced Concrete Structures** *Room: Strand 13B*

Technical Presentations

The following pages contain concurrent session titles, titles of presentations, and names of authors (presenters' names underlined).

DAY 1
SATURDAY MARCH 23, 2024
SATURDAY 8:00 a.m.–10:00 a.m.

Session 1: FRP Bond and Anchorage in Concrete Structures

Moderators: Maria M. Lopez and Ravi Kanitkar
Room: Strand 12B

Proposed Design Method for EB-FRP Ties Debond Strain Encompassing Short/Long and Thin/Thick Ties
Junrui Zhang, Enrique del Rey Castillo, Ravi Kanitkar, Aniket D Borwankar, and Ramprasath R

Review and Analysis of FRP Bond Lengths from Pull-out Testing Database with Reduced Embedment Lengths
John Myers

Evaluation of the Bond Performance of Concrete-Epoxy Interface Using Segmentation-Based Image Processing Techniques
Abubakar S. Ishaq, Maria M. Lopez, Charles E. Bakis, and Yoseok Jeong

Behavior of Partially Bonded GFRP-Reinforced Concrete Beams
Ali Alatify and Yail Kim

Bond of FRP and NSM Bars to Alkali-activated Mortar Combining Blast Furnace Slag and Waste Glass
Ivana Krajnović, Stijn Matthys, Bryan Barragán, Léo Bos and Gérard Tardy

Session 2: Strengthening of Concrete Structures Using FRP Systems

Moderators: Ayman M. Okeil and Tarek Alkhrdaji
Room: Strand 13B

Effectiveness of Using Dowelled GFRP Bars to Repair Reinforced Concrete Bridge Barriers
Juan Torres Acosta and Douglas Tomlinson

A New Bond Model for RC Beams Strengthened with Embedded Through-Section Method
Sara Mirzabagheri, Andrew Kevin Kenneth Doyle, Amir Mofidi, and Omar Chaallal

Shear Behavior of 60-Year-Old Bridge Girder Strengthened Using CFRP Sheets
Mohamed Ahmed, Slimane Metiche, Radhouane Masmoudi, Richard Gagne, and Jean- Philippe Charron

Assessment of the Existing Shear Resistance Models for RC Beams Strengthened with Near Surface-Mounted FRP Reinforcement
Amirhossein Mohammadi, Joaquim A.O. Barros, José Sena-Cruz, and Salvador J.E. Dias

Evaluation the Predicted Shear Strength of Concrete Deep Beams Reinforced with FRP Bars
Eklas Hatto Hashim and Hassan Falah Hassan

SATURDAY 10:30 a.m.–12:30 p.m.

Session 3: FRP Materials: Properties, Tests and Standards

Moderators: John Myers and Charles E. Bakis
Room: Strand 12B

Physical and Mechanical Properties of Helical Wrap GFRP Bars for Reinforcing Concrete Structures
Girish Narayan Prajapati, Shehab Mehany, Wenxue Chen, and Brahim Benmokrane

Interface Shear Transfer Mechanism with GFRP Bars Reinforcement
Camilo Vega, Abdeldjelil Belarbi, and Antonio Nanni

An Effective Simple Fixture for Testing GFRP Rebars in Compression
Alireza Sadat Hosseini and Pedram Sadeghian

Session 4: Emerging FRP Systems and Successful Project Applications

Moderators: Pedram Sadeghian and Radhouane Masmoudi
Room: Strand 13B

Numerical Design Optimization of a New Hybrid-Utility Pole
Mohamed Bouabidi, Slimane Metiche, and Radhouane Masmoudi.

A Novel VOC-Free Epoxy System for High Modulus Glass Fiber Reinforced Polymer Rebar
Huifeng Qian and Wendell Harriman II

Monitoring of RC Beams Using SMART FRP Bonded Material
Ferrier Emmanuel, Laurent Michel, and Andrea Armonico

Durability of a Solid Slab Bridge with Overlays Incorporating BFRP

Exploring Strength of Straight and Bent GFRP Bars: Refinements to CSA S807:19 Annex E
Ahmed Khalil, Rami A. Hawileh, and Mousa Attom

Convertible Bond Test Apparatus for EB FRP, NSM FRP, FRCM, and Allied Systems: Proof of Concept
Faisal Mukhtar

Grids
Jun Wang and Yail J. Kim

Sustainable Marine Infrastructure Enabled by the Innovative Use of Seawater Sea-Sand Concrete and Fibre-Reinforced Polymer Composites
Tao Yu and Jin-Guang Teng

Fatigue Behavior of CFRP Sheets Attached to Concrete Surface by Using EBROG Strengthening Method
Mehdi Khorasani, Giovanni Muciaccia, and Davood Mostofinejad

SATURDAY 1:00 p.m.–3:00 p.m.

Session 5: FRP-reinforced Concrete Structures

Moderators: Pedram Sadeghian and Douglas Tomlinson
Room: Strand 12B

Assessment of the Flexural Bond Stresses of New Generation GFRP bars
Jesús D. Ortiz, Zahid Hussain, Seyed-Arman Hosseini, Brahim Benmokrane, and Antonio Nanni

Evaluation of ACI 440.11 Shear Strength Provisions for Members without Stirrups
Stephanie L. Walkup, Eric S. Musselman, Shawn P. Gross, and Hannah Kalamarides

Structural and Deformational Behavior of Flexural Concrete Beams Reinforced with GFRP and BFRP Rebars
Raphael Kampmann, Tim Rauert, Niklas Pelka, and Bastian Franzenburg

Open Issues on the Structural Performances of Concrete Beams Reinforced with FRP (Fiber Reinforced Polymers) Rebars
Maria Antonietta Aiello and Luciano Ombres

Session 6: FRP Design Codes and Guidelines

Moderators: Ayman M. Okeil and Maria M. Lopez
Room: Strand 13B

Recent FRP Code Developments in the United States for Reinforcing and Strengthening Concrete Structures
Maria Lopez de Murphy

Canadian Codes on FRP and the underlying Research and Field Applications
Shamim Sheikh

Design of FRP-reinforced Concrete Structures in Europe
Tommaso D'Antino

Discussion of FRP Design Codes and Guidelines in Brazil and South America
Daniel Carlos Taissum Cardoso

Engineering Practices for the use of FRP in Latin America - The Role of the Codes and Guidelines
Gustavo Tumialan

Recent FRP Code Developments in China for Reinforcing and Strengthening Concrete Structures
Peng Feng

SATURDAY 3:30 p.m.–5:30 p.m.

Session 7: Advances in FRP Applications in Masonry Structures

Moderators: John Myers and Gustavo Tumialan
Room: Strand 12B

Experimental efficiency of FRP bars as injected anchors for masonry structures
Francesca Ceroni, Alberto Balsamo, and Marco Di Ludovico

Out of plane Strengthening of Masonry Walls with Inorganic Composites
Marta Del Zoppo, Marco Di Ludovico, Alberto Balsamo, and Andrea Prota

Session 8: Seismic Resistance of FRP-Reinforced/Strengthened Concrete Structures

Moderators: Maria Lopez de Murphy and Pedro F. Silva
Room: Strand 13B

Modeling Cyclic Response of CFRP Strengthened Fiber Anchored RC Frame Members to Failure
Salman Alshamrani, Sama Mohammed Saleem, Hayder A. Rasheed, and Fahed H. Salahat

A Comparative Analysis of GFRP- and Steel-RC Columns under Combined Shear, Flexure, and Torsion Loads
Yasser M. Selmy and Ehab F. El-Salakawy

Discontinuous FRCM-confinement of Masonry Columns
Alessio Cascardi, Salvatore Verre, and Luciano Ombres

Performance of CFRP Anchors and In-fill Blocks in Shear Strengthening of I-sections
Muhammad Arslan Yaqub, Christoph Czaderski, and Stijn Matthys

Use of CFRP Rebars As Retrofitting System for Masonry Panels
F. Ferretti, A. R. Tilocca, A. Incerti, S. Barattucci, and M. Savoia

Seismic Strengthening of RC Beam-Column Joints with FRP Systems Applicable from the Exterior of the Building
Ciro Del Vecchio, Marco Di Ludovico, Alberto Balsamo, and Andrea Prota

Development of ASCE41 m-Factors for FRP Strengthened Columns
Pedro F. Silva and Tarek Alkhrdaji

Numerical Investigation and Experimental Plan on Seismic Performance of Carbon Fiber-Reinforced Polymer-Reinforced Concrete Columns
Chaoran Liu, Ligang Qi, Ying Zhou, Guowen Xu, Yan Yang, Zhiheng Li, and Yiqiu Lu

DAY 2
SUNDAY MARCH 24, 2024
SUNDAY 8:00 a.m.–10:00 a.m.

Session 9: FRP Bond and Anchorage in Concrete Structures
Moderators: Maria M. Lopez and Baolin Wan
Room: Strand 12B

Bond Performance of CFRP-Concrete Joints Subjected to Freeze-Thaw Cycles: Experimental Study and Analytical Analysis
Ahmed Kallel, Radhouane Masmoudi, Benoit Bissonnette and Marcelin Joanis

Model Uncertainty in Reliability Analysis of FRP-To-Concrete Bond with Grooves
Zhao Wang and Baolin Wan

Fracture Energy of GFRP-Concrete Bonded Interface after Sustained Loading in Natural Environments
Jaeha Lee, Kivanc Artun, Charles E. Bakis, Maria M. Lopez and Thomas E. Boothby

Bond-Deteriorated Reinforcement Concrete Beams Strengthened with CFRP
Riliang Li and Riyad S Aboutaha

Data-Driven Prediction of The Bond Coefficient Between Fibre-Reinforced Polymer (FRP) Bars and Concrete
Nadia Nassif, M. Talha Junaid, Salah Altoubat, Mohamed Maalej, and Samer Barakat

Session 10: Behavior and Design of Prestressed Concrete Structures
Moderators: John Myers and Abdeldjelil Belarbi
Room: Strand 13B

Deflection Behavior of Beams Prestressed with Bonded FRP Tendons
Wassim Nasreddine, Peter H. Bischoff, and Hani Nassif

Flexural behavior of Concrete Beams Prestressed with Hybrid Tendons
Adi Obeidah and Hani Nassif

Application of FRP in the Rehabilitation of Prestressed Concrete Girder Bridges
Ramin Rameshni, Reza Sadjadi, and Melanie Knowles

The Performance of Prestressed Carbon Fibre Reinforced Polymer (CFRP) Bridge Tendons after 18 Years in Service
Alexandra Boloux, Luke Bisby, Valentin Ott, Giovanni P. Terrasi

Flexural Strength and Behavior of Inverted-T Precast Concrete Beam Reinforced with Smooth CFRP Bars
Mohd Basri Che Bakar, Raizal Saifulnaz Muhammad Rashid, and Mohd Saleh Jaafar

SUNDAY 10:30 a.m.–12:30 p.m.

Session 11: FRP Use in Column Applications
Moderators: Pedram Sadeghian and Hayder A. Rasheed
Room: Strand 12B

Biaxial Interaction Diagrams of Elliptical Concrete Column Sections Reinforced with GFRP Bars

Session 12: Effects of Extreme Events on FRP-Reinforced/Strengthened Structures
Moderators: Maria M. Lopez and Mark Green
Room: Strand 13B

Experimental Assessment of Large-Scale FRP-Strengthened RC Shear

Ahmad Ghadban and Hayder A. Rasheed

Stress-strain Model of Concrete Confined by FRP Laminate and Spike Anchors
Zhibin Li, Enrique del Rey Castillo, Richard S. Henry, Kent A. Harries, and Tongyue Zhang

Failure Characterization of GFRP-Reinforced Concrete Walls
Ju-Hyung Kim and Yail J. Kim

Evaluation of Hysteretic Energy and Damping Capacity of GFRP-RC Columns Under Cyclic Loading
Yasser M. Selmy, Amr E. Abdallah, and Ehab F. El-Salakawy

Strengthening of Rectangular Reinforced Concrete Columns Using CFRP
Salah Abd-elgawad Aly

Controlled Walls Subjected to Cyclic Loads
Sheng-Hsuan Lin, Insung Kim, Ravindra Kanitkar, Garrett R. Hagen, Griffith L. Shapack, and Aniket D. Borwankar

PBO FRCM Composite System Exposed to Elevated Temperatures: Experimental and Theoretical Investigations
Luciano Ombres, Pietro Mazzuca, Alfredo Micieli, and Francesco Campolongo

The Implementation of Fire Resistance Recommendations in ACI Code-440.11
Hamzeh Hajiloo, Mark Green, and Bronwyn Chorlton

Active Strengthening with Post-Tensioned CFRP Tendons
Eri Vokshi and Marcel Rey

Seismic Performance of Concrete Beam-Column Joints Reinforced with Carbon Fiber-Reinforced Polymer (CFRP) Bars and Stirrups
Ligang Qi, Guohua Cen, Chaoran Liu, Ying Zhou, Guowen Xu, Yan Yang, Zhiheng Li, and Yiqiu Lu

Seismic Confinement of Brick Masonry Structure with CFRP
Ahmad Saboor, Khyber Kplwak, Imad Ahmed and Samiullah Qazi

SUNDAY 1:00 p.m.–3:00 p.m.

Session 13: Durability of FRP Systems

Moderators: Ayman M. Okeil and Christian Carloni
Room: Strand 12B

Freeze-Thaw Durability of GFRP and BFRP Rebars
Raphael Kampmann, Carolin Martens, Srichand Telikapalli, and Alvaro Ruiz Emparanza

Assessment of Crack Spacing and Crack Width Formulations in RC Elements Externally Strengthened with FRP Materials
Francesca Ceroni, Cristina Barris and Alejandro Perez Caldentey

Quasi-Static and Fatigue Behavior of GFRP Bars Embedded in Concrete: A Comparison Between Pull-Out Tests and Flexural Tests of Slabs
Charles Tucker Cope III, Mohammod Minhajur Rahman, Francesco Focacci, Tommaso D'Antino, Iman Abavisani, and Christian Carloni

Fatigue Performance of Real-Scale Precast GFRP Reinforced Lightweight Concrete Arches
Bartosz Piątek and Tomasz Siwowski

Fatigue Performance under Rolling Load of Full-Scale Concrete Bridge Deck with GFRP Stay-In-Place Form
Amir Fam and Chongxi Gao

Session 14: Advanced Analysis of FRP Reinforced Concrete Structures

Moderators: Pedram Sadeghian and Maria Anna Polak
Room: Strand 13B

Analysis of Concrete Deep Beams with Fibre-Reinforced Polymer (FRP) Bars by Indeterminate Strut-and-Tie (IST) Method
Shuqing Liu and Maria Anna Polak

Effect of Weathering Exposure Time on the Flexural Behavior of FRP Strengthened RC Beams
Haitham A. Ibrahim, Mohamed F. M. Fahmy, and Seyed Saman Khedmatgozar Dolati

Finite Element Analysis of the Interface between FRP and Concrete
Todor Zhelyazov, Eythor Rafn Thorhallsson, and Jonas Thor Snaebjornsson

A Review of Strut-and-Tie Models for FRP Reinforced Deep Beams
Taylor J. Brodbeck, Giorgio T. Proestos, and Rudolf Seracino

Paper Abstracts

Proposed Design Method for EB-FRP Ties Debond Strain Encompassing Short/Long and Thin/Thick Ties

Junrui Zhang, Enrique del Rey Castillo, Ravi Kanitkar, Aniket D Borwankar, and R Ramprasath

A systematic literature review was conducted on pure tension strengthening of concrete structures using fiber-reinforced polymer (FRP), specifically for larger FRP tie applications. This work yielded a dataset of 1,627 direct tension tests, and highlighted the limitation of existing studies on studying thick and long FRP ties, which are typical in real construction scenarios. To overcome this shortcoming, 51 single lap shear tests were conducted on thicker and longer FRP ties, with the dimensions being 0.5 to 6 mm [0.02 to 0.24 in.] thickness, and 300 to 1,524 mm [12 to 60 in.] long. The critical parameters under consideration were concrete compressive strength, FRP thickness, and bond length. The findings demonstrate that thicker and therefore stiffer FRP ties have higher debond force capacity, while longer ties exhibit greater post-elastic deformation capacity but do not affect the debond force capacity. Concrete had a limited effect on either debond force or deformation capacity. A strength model is proposed for FRP systems under axial pure tension, which aligns well with both the published and tested results. This paper focuses on the development of design guidelines and codes to predict the debond strain for EB-FRP systems incorporating thicker and longer FRP ties, aiming to enhance the applicability of FRP to real-world construction scenarios.

PBO FRCM Composite System Exposed to Elevated Temperatures: Experimental and Theoretical Investigations

Luciano Ombres, Pietro Mazzuca, Alfredo Micieli, and Francesco Campolongo

This paper presents experimental and theoretical investigations on the residual tensile and bond response of polypara-phenylene-benzo-bisthiazole (PBO) fabric reinforced cementitious matrix (FRCM) composites after the exposure to elevated temperatures ranging between 20 °C [68 °F] and 300 °C [572 °F]. Experimental results obtained from direct tensile (DT) and single-lap direct shear (DS) tests carried out respectively on PBO FRCM specimens and PBO FRCM-concrete elements were reported and discussed. Overall, specimens exposed to temperatures up to 200 °C [392 °F] did not present significant reductions of both bond and tensile properties. This result can be attributed to the thermal shrinkage underwent by the inorganic matrix, which may enhance the bond between the fibers and the matrix. On the other hand, when the specimens were heated at 300 °C [572 °F], marked reductions were observed, primarily stemming from the degradation of both mechanical properties of the FRCM constituent materials and the fiber-to-matrix bond. Subsequently, the experimental results were used for the following purposes: (i) to assess whether the Aveston–Cooper–Kelly (ACK) theory is able to describe the tensile behavior of FRCM materials at elevated temperatures; (ii) to define temperature-dependent local bond stress vs. slip law and (iii) to evaluate the ability of degradation models to simulate the variation with temperature of the FRCM tensile and bond properties. The results obtained from the theoretical analyses showed that, for all the tested temperature, the relative differences between predicted and experimental results are very low, confirming the accuracy of the proposed approaches.

Assessment of the Flexural Bond Stresses of New Generation GFRP bars

Jesús D. Ortiz, Zahid Hussain, Seyed-Arman Hosseini, Brahim Benmokrane, and Antonio Nanni

As a result of the limited data available when the current ACI 440.11-22 development length equation was developed, certain parameters were disregarded. Additionally, the equation was based on bars that are no longer in use today, and significant advancements have been made in FRP material properties and production methods since its calibration. Conflicting research findings have led to differing perspectives on its reliability, with some suggesting it yields overly conservative results, while others argue it may overestimate bond strength. To address this concern, an experimental study was conducted to assess the bond stresses between GFRP bars and conventional concrete in under-reinforced concrete beams. The beams were reinforced using a single M16 (No.5) Glass/Vinyl-ester FRP sand-coated bar. Three different lap splice lengths (i.e., 40-, 60-, and 80-times bar diameter) were selected based on available literature. The results indicate that the bond is primarily governed by surface friction, with negligible impact from relative slippage. The lap-spliced specimens exhibited slippage failure but exceeded design moments based on ACI provisions, indicating efficient performance. Stiffness remained comparable to that of the un-spliced beam, suggesting intact bond capacity despite some slippage. Average bond stress calculations closely aligned with ACI maximum bond stress values. Overall, the study offers valuable insights into GFRP bar behavior and bond capacity.

Seismic Confinement of Brick Masonry Structure with CFRP

Ahmad Saboor, Khyber Kplwak, Imad Ahmed, and Samiullah Qazi

This research study explores the impact of carbon fiber-reinforced polymer (CFRP) in enhancing the strength of a traditional residential masonry structure. Previous studies have focused on strengthening masonry cantilever walls with CFRP, but these walls do not accurately mimic the seismic behavior of an entire masonry *structure. Some studies have also examined modified masonry structures with added openings in parallel walls to counteract torsion caused by differences in stiffness. However, these modifications deviate from the representation of a real rural structure. The present research specifically targets typical rural structures found in central Asia, where approximately ninety percent of masonry buildings lack reinforcement and are vulnerable to seismic activity. Given the circumstances, it becomes crucial to strengthen these structures using an economical, efficient, and feasible technique. Partial bonding with CFRP proves to be more cost-effective than complete jacketing. However, it is prone to issues such as interface delamination. Consequently, this research employs the partial bonding technique along with a CFRP anchorage system only on the walls external side. Two unreinforced masonry (URM) structures resembling a typical village room are constructed for testing purposes at a one-third scale. The specimens were subjected to displacement controlled lateral load along with a constant vertical load. The CFRP strengthened specimen performed well in terms of observed failure modes, load response curve, and seismic performance levels as compared to URM structure.*

Experimental efficiency of FRP bars as injected anchors for masonry structures

Francesca Ceroni, Alberto Balsamo, and Marco Di Ludovico

Masonry structures are very sensitive to out-of-plane mechanisms under horizontal actions. A common traditional technique to avoid or mitigate the activation of these mechanisms is represented by injected anchors made of steel bars aimed to improve the connections between orthogonal masonry walls or between floors and masonry walls. The bars are usually embedded in the masonry by means of cement-based grout in holes realized inside the elements to be connected. Recently, an increased interest has developed in the scientific community about the use of Fiber Reinforced Plastic (FRP) bars as alternative to the steel ones for injected anchors, mainly because of their high tensile strength and inertia to corrosion, which can give them high durability, in addition to the use of high-performance grouts. The paper reports the results of experimental pull-out tests realized by the Authors on several types of FRP bars used as injected anchors in small masonry specimens made of yellow tuff blocks. A hydraulic lime and pozzolana-based grout is used to fix the bars in holes realized in the masonry specimens along an embedded length of 250 mm. The set-up is realized in order to apply pure tension to the bars and shear stresses along the bar-grout and the grout-masonry interfaces. The results are analyzed in terms of maximum pull-out forces, failure modes and force-displacement relations in order to evidence the global performance of each tested system, especially in relation with the diameter and the surface treatment of the bars. Some comparisons with literature formulation for predicting the pull-out force are developed too.

Bond of FRP and NSM Bars to Alkali-activated Mortar Combining Blast Furnace Slag and Waste Glass

Ivana Krajnović, Stijn Matthys, Bryan Barragán, Léo Bos and Gérard Tardy

The use of fiber reinforced polymers (FRPs) as concrete reinforcement is a good alternative amongst other in places where corrosion of steel is eminent, , or where non-conductivity is of importance. Furthermore, over the last 30 years, FRPs became the state-of-the-art materials for strengthening and seismic retrofitting of concrete and masonry structures. Near surface mounted (NSM) FRPs is one of the techniques for structural repair of deficient concrete elements. It usually comprises of high-strength FRP rebars made of carbon, alkali-resistant (AR) glass, basalt, aramid and typically bonded with organic epoxy resin. Utilization of epoxy comes with certain drawbacks like inability to be applied on wet surfaces, lack of gas permeability, low performance under fire and high costs, that more and more researchers are exploring utilization of inorganic materials like Portland cement (PC) or alkali-activated materials (AAMs). AAMs are emerging as a future-proof technology in the palette of more eco-friendly concrete production technologies, as they combine utilization of industrial by-products and omission of Portland cement clinker, maximizing environmental benefits of structures. Bond between FRPs and inorganic system is crucial factor for combination of these two systems either in reinforced concrete structures or for strengthening purposes. The purpose of this research is to check the potential usage of previously developed AAM with FRP rebars in structural and strengthening applications, by focusing in this study on the bond behavior between FRP and different inorganic matrixes. The verification of bond properties of the AAM with glass FRP (GFRP) and carbon FRP (CFRP) bars are evaluated through pull-out rebar test and modified NSM pull-out test. Two bond lengths are considered. Comparison with PC mortar mix for most of the performed pull-out tests is presented as well.

Performance of CFRP Anchors and In-fill Blocks in Shear Strengthening of I-sections

Muhammad Arslan Yaqub, Christoph Czaderski, and Stijn Matthys

Performance of carbon fiber reinforced polymers (CFRP) strengthening systems basically depends on the bond between CFRP and the concrete substrate. Particularly, in case of shear strengthening of I-shaped cross sections, this bond is inefficient due to the concave shape of this specific cross section. This will typically cause early debonding at the web-flange corners resulting in limited increase in the shear strength. This paper reports, as part of wider experimental campaign, the results of three shear strengthening configurations over I-sections using CFRP spike anchors or epoxy bonded in-fill concrete blocks. It is observed that CFRP spike anchors at the web-flange corners, for the tested configurations, helped in increasing the performance of the shear strengthening system up to 13%, whereas, with the use of epoxy bonded in-fill concrete blocks and spike anchors in the compression zone the performance of the shear strengthening system was improved up to 23%. The latter system proved to be very effective as debonding around the web-flange corner was eliminated.

Deflection Behavior of Beams Prestressed with Bonded FRP Tendons

Wassim Nasreddine, Peter H. Bischoff, and Hani Nassif

The use of FRP tendons has become an attractive alternative to steel tendons in prestressed concrete structures to avoid strength and serviceability problems related to corrosion of steel. There is however a lack of knowledge in serviceability behavior related to deflection after cracking for beams prestressed with FRP tendons. Conventional approaches used to compute deflection of cracked members prestressed with steel is problematic at best, and the situation is exacerbated further with the use of FRP tendons having a lower modulus of elasticity than steel. Deflection of FRP reinforced (nonprestressed) concrete flexural members computed with Branson's effective moment of inertia requires a correction factor (called a softening factor) that reduces the member stiffness sufficiently to provide reasonable estimates of post-cracking deflection. For FRP prestressed concrete however, this approach does not always work as expected and deflection can be either underestimated or overestimated significantly. This study investigates the accuracy of different models proposed for estimating deflection of cracked FRP prestressed members using a database of 38 beams collected from the literature. All beams are fully prestressed. Results indicate that using Branson's effective moment of inertia with a generic softening factor can produce reasonable estimates of deflection provided the response is shifted up to the decompression moment or adjusted with an effective prestress moment defined by an effective eccentricity of the prestress force. The former approach overpredicts deflection by 20% on average while the latter overpredicts deflection by not more than 5% based on the beams available for comparison. Assuming a bilinear moment deflection response overpredicts deflection by 12%, while an approach proposed by Bischoff (which also shifts the response upwards) overpredicts deflection by 23%. These last two approaches work reasonably well without the need for a correction factor.

Numerical Design Optimization of a New Hybrid-Utility Pole

Mohamed Bouabidi, Slimane Metiche, and Radhouane Masmoudi

The current market of utility poles is growing rapidly. The dominant materials that are used for this purpose are generally wood, steel, concrete, and fiber-reinforced polymers (FRP). FRP poles are gaining wide acceptance for what they provide in terms of strength and durability, lack of maintenance and a high strength to weight ratio. Hybrid structures can combine the best properties of the materials used, where each part enhances the structure to provide a balanced structure. This study evaluates a hybrid structure composed of three main layers, an outer FRP shell, a hollow concrete core and an inner hollow steel tube, this whole system is to be utilized as a tapered utility pole. The outer FRP shell provides protection and enhances the strength of the pole, the concrete core provides stiffness, and the inner steel tube enhances the flexural performance while reducing the volume in consequence the weight of the structure compared to a fully filled pole. A new design for a 12-feet long hybrid FRP pole using finite element is presented in this paper. The design was based on a parametric study evaluating the effect of key-design parameters (i.e., the thickness of FRP, the volume and strength of the concrete, the thickness and diameter of the steel tube). Concrete strength affected the general performance of the pole, the decrease in concrete strength due to utilizing lightweight concrete was compensated with increasing the FRP pole thickness. For the same pole configuration, with incremental variation of the FRP thickness values from 3 mm to 7 mm up to the initial concrete cracking load, no significant variation of the pole top deflection was observed. However, at failure load the increase of FRP thickness from 3 mm to 7 mm decreased the ultimate tip deflection by 50%. New hybrid utility poles have the potential to be an interesting alternative solution to the conventional poles as they can provide better durability and mechanical performances.

Strengthening of Rectangular Reinforced Concrete Columns Using CFRP

Salah Abd-elgawad Aly

Rectangular reinforced concrete (RC) columns with aspect ratio up to one-to-five are commonly used in residential buildings. Wrapping rectangular RC columns with external carbon fiber reinforced polymer (CFRP) are introduced in this research to increase its axial capacity as well as the ductility. The strength enhancement of these columns arises from two sources. First, the confinement effect of transverse fiber sheets leads to an increase in the uniaxial compressive strength of the confined concrete resulting subsequently in an increase in the contribution of concrete to the load-carrying capacity of the column. Second, the longitudinal fiber sheets contribute directly to the load-carrying capacity of the column. Wrapping circular columns with CFRP has been proven to be a very effective method to increase both the axial capacity and ductility of columns. However, it is less effective for square columns and much less effective for rectangular columns. This is attributed to less confinement of the columns due to the out-of-plane deformation of the laminates, induced by the axial loads on columns. A total of 8 half-scale, short columns were fabricated and tested to failure under a concentric load to investigate the effect of CFRP configuration on the strength enhancement of the columns, and a simple analytical approach is used to evaluate the axial load-carrying capacity of the strengthened columns. Each column had across-sectional dimension measuring 120 by 480 mm, with an aspect ratio of 4.0, overall height of 1940 mm, and a clear height of 1500 mm. The study revealed that the strengthening technique is expected to effectively enhance the efficiency of the CFRP strengthening technique, especially for columns with rectangular sections as the area of the well-known dead zone of these columns is reduced using the proposed technique. Also, the results proved that the efficiency of strengthening tested columns by CFRP jacket has been enhanced using the strengthening technique by about 71% of original RC columns, which exceeds the traditional method (Jacket) CFRP wrap by 60%. Different recommendations of rectangular RC columns strengthened by using CFRP are introduced.

Freeze-Thaw Durability of GFRP and BFRP Rebars

Raphael Kampmann, Carolin Martens, Srichand Telikapalli, and Alvaro Ruiz Emparanza

While reinforced concrete is one of the most used construction materials, traditional reinforcement steel may cause undesirable side effects, as corrosion and the associated volume changes can lead to damages in the concrete matrix and can cause spalling, which may significantly reduce the load-bearing capacity and service life of structures. Alternative reinforcement methods, such as glass or basalt fiber reinforced polymer rebars, can serve as a viable alternative to reduce or eliminate some of the disadvantages associated with steel reinforcement. In addition to an increased tensile strength and a reduction in weight, fiber reinforced polymer rebars also offer a high corrosion resistance among other beneficial properties. Because these materials are not fully regulated yet and the durability properties have not been conclusively determined, further research is needed to evaluate the material durability properties of FRP rebars. To determine the durability properties of GFRP and BFRP rebars in cold climates, the freeze-thaw resistance of these materials was evaluated throughout this study. Specifically, two types of materials (basalt and glass reinforced polymers) and two common rebar sizes (8 mm (#2) and 16 mm (#5) diameters) were tested. To quantify the freeze- thaw-durability, tensile tests according to ASTM D7205, transverse shear strength tests in line with ASTM D7617, and horizontal shear strength tests as specified in ASTM D4475 were conducted on numerous virgin fiber rebars and on fiber rebars that were subjected to 80 and 160 freeze-thaw cycles. While the results from the virgin materials served as benchmark values, the measurements and analysis from the aged (by freeze-thaw cycles) materials were used to quantify and determine the strength retention capacity of these bars. The results showed that a higher number of freeze-thaw cycles lead to lower strength retention for some rebar types. In addition, it was seen that rebar products respond differently to the aging process; while some material properties notably deteriorated, other material properties were insignificantly affected.

Assessment of Crack Spacing and Crack Width Formulations in RC Elements Externally Strengthened with FRP Materials

C. Barris, F. Ceroni, and A. Perez Caldentey

Serviceability checks in Reinforced Concrete (RC) elements involves the verification of crack width mainly aimed to limit the exposure of the steel reinforcement to corrosion and chemical attack and, thus, improve durability. Classical approaches for assessing the crack width in RC elements provide the calculation of two terms: 1) the average crack spacing, and 2) the average difference between the strain in the steel reinforcement and in the concrete in tension referred to the average crack spacing. A similar approach can be assumed valid also for RC elements strengthened with externally bonded Fiber Reinforced Polymer (FRP) materials, taking into account the additional tension stiffening effect provided by the external reinforcement. This paper presents the comparisons of some existing code formulations for predicting crack spacing and crack width in RC elements with the experimental results of a database collected by the Authors and concerning tests on RC beams and ties externally bonded with different types and configurations of FRP materials. The paper is mainly aimed to check the reliability of the existing equations provided by codes in order to address the future assessment of reliable design provisions for cracking verifications in RC elements strengthened with FRP materials. The comparisons have evidenced, indeed, some useful issues for the design provisions: 1) larger scatter in the predictions of crack width than in crack spacing and, in particular, for ties, 2) limited effect of shrinkage on crack width, 3) necessity of taking into account the external reinforcement in crack spacing formulations, 4) good reliability of mechanical models for calculating cracks width.

Review and Analysis of FRP Bond Lengths from Pull-out Testing Database with Reduced Embedment Lengths

John J. Myers

The American Concrete Institute (ACI) 440.1R-15 Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars linearly reduces the bar stress and thereby pull-out capacity of FRP bars to zero from an embedment length at 20 bar diameters (db) or less. Most experimental research and data examine the development length of various FRP bars at longer, more traditional, embedment lengths. A database was created from select available data in literature to compare to empirical standards. This investigation examines the bond performance of short embedded FRP bars into concrete considering a pull-out failure mode to expand the understanding of short embedded FRP bars into concrete. Based upon the database collected, for the glass fiber-reinforced polymer (GFRP) rebars, the current 440.1R appears quite conservative. For the basalt fiber-reinforced polymer (BFRP) rebar database collected, the current ACI 440.1R-15 provisions appear unconservative for a statistically significant number of the specimen test results within the database. In the case of the carbon fiber-reinforced polymer (CFRP) database, which is quite limited, the data appears to develop considerably less bond strength than the current 440.1R provisions might suggest which requires deeper investigation for the case of short embedment length bonded CFRP bars.

Effectiveness of Using Dowelled GFRP Bars to Repair Reinforced Concrete Bridge Barriers

Juan Torres Acosta and Douglas Tomlinson

Three bridge barriers were tested under pseudo-static loading to assess the effectiveness of a dowelling repair technique for restoring the capacity of damaged glass fiber-reinforced polymer (GFRP) reinforced systems. Barriers were 1500 mm (59.1 in.) wide and tested with an overhang of 1500 mm (59.1 in.). One barrier was entirely reinforced with steel reinforcement with the layout and geometry common in Alberta, Canada for highway applications. A second barrier replaced all steel reinforcement with GFRP bars. The third barrier simulates repair where the barrier is damaged and needs to be replaced by removing the barrier, drilling holes, and

using epoxy to dowel GFRP bars into the deck. All barriers failed by concrete splitting at the barrier/deck interface which is attributed to the complex interaction of stresses from the barrier wall and overhang. The steel reinforced barrier was strongest but had slightly lower energy dissipation than the GFRP reinforced barriers. The repaired GFRP reinforced barrier had very similar response to the baseline GFRP reinforced barrier but reached a slightly larger capacity. Previously completed finite element models showed similar general responses and failure modes but larger stiffnesses and strengths than the tests which requires further investigation.

Quasi-Static and Fatigue Behavior of GFRP Bars Embedded in Concrete: A Comparison Between Pull-Out Tests and Flexural Tests of Slabs

Charles Tucker Cope III, Mohammod Minhajur Rahman, Francesco Focacci, Tommaso D'Antino, Iman Abavisani, and Christian Carloni

GFRP bars are considered an alternative to steel for concrete reinforcement. This project investigated the fatigue behavior of GFRP bars embedded in concrete, studying bond behavior at material and structural scales. GFRP bars (12 mm [0.47 in.] nominal diameter) were embedded in concrete cylinders leaving a 50 mm [2 in.] protrusion at the free end and featuring different bonded lengths. Two types of GFRP bars with different surface treatment (lacquered and unlacquered) were used. Static tests were used to determine the bonded length required for cyclic pull-out tests, Cyclic tests at 1.5 Hz showed GFRP bar failure was possible at just 20% of their reduced tensile strength (0.8ffu) as prescribed in ACI 440.1R-15. Two full-scale slabs internally reinforced with unlacquered GFRP bars were tested using a four-point bending configuration. A quasi-static test was used as a control to determine the fatigue amplitude, considering the fatigue loading provided by the ACI 440.1R-15 document and the pull-out test results with cyclic loading presented in this work. Cyclic load between 10 kN [2.25 kips] and 40 kN [9 kips] at a 1.5 Hz frequency was applied up to 5 million cycles before a subsequent quasi-static test was conducted. The load range was determined using cross-section analysis to cycle the bars between 5% and 20% of their reduced tensile strength (0.8ffu). Both slabs ultimately failed due to shear failure, with cyclic loading having little impact on the slab compliance. Displacements of the load points and supports were measured using linear variable displacement transformers (LVDTs), while digital image correlation (DIC) was utilized to obtain the full-field displacement and strain in the central region of the slab. The strain and displacement fields from DIC were used to determine the opening of flexural cracks and relate it to the stress level in the GFRP bars. A comparison between the static pull-out tests and the four-point bending tests of slabs indicated that the pull-out test could be used to describe the flexural behavior of the slab at low stress level. However, in terms of fatigue behavior, the comparison between the small- and large-scale tests indicated that the fatigue phenomenon in the slab was quite complex and could not be directly described by the results of pull-out tests.

A New Bond Model for RC Beams Strengthened with Embedded Through-Section Method

Sara Mirzabagheri, Andrew Kevin, Kenneth Doyle, Amir Mofidi, and Omar Chaallal

Embedded Through-Section (ETS) method is a shear rehabilitation technique for concrete structures involving pre-drilling vertical holes into a reinforced concrete member and installing FRP bars to be bonded using epoxy adhesive. Due to the lack of reliable models for predicting the ETS FRP bond behavior, developing an accurate model to predict the maximum pull-out force of the ETS technique was deemed a knowledge gap. In this study, the main parameters used in an analytical bond-slip model proposed by the authors were obtained empirically and evaluated against the existing experimental results in the literature. To be able to calculate the maximum pull-out force for ETS FRP bars with different materials, a fracture mechanics-based bond model was defined in terms of the joints' geometrical and material properties, to allow the model to predict the performance of any FRP type with any concrete compressive strength. By using data in the available literature on FRP ETS pull-out tests, statistical analysis was utilized to fit the parameters against experimental data. The proposed model was able to produce superior analytical predictions of the experimental test data when compared to the existing bond models for ETS FRP bars.

Monitoring of RC Beams Using SMART FRP Bonded Material

Emmanuel Ferrier, Laurent Michel, and Andrea Armonico

This paper presents the crack monitoring of reinforced concrete beams strengthened with fiber reinforced polymer (FRP) sheets. Emphasis is placed on the development of a smart FRP bonded material that can measure the crack opening of a reinforced concrete beam strengthened by FRP. The reliability measured by a conventional digital image correlation (DIC) and by the proposed smart FRP is employed to assess the contribution of the FRP to control the crack. The monitoring process is based on a large set of experimental database consisting of 19 test beams. The effect of FRP to control the crack opening is studied depending on the steel ratio, FRP ratio and the level of damaged of RC beams when FRP is applied. The results were compared with the theoretical values of crack width and spacing predicted using the Eurocode 2 (EC2) formula, calibrated for non-strengthened RC elements. The corresponding results were compared in order to clarify the effect of external bonded FRP on the cracking behaviour of RC beams.

Seismic Performance of Concrete Beam-Column Joints Reinforced with Carbon Fiber-Reinforced Polymer (CFRP) Bars and Stirrups

Ligang Qi, Guohua Cen, Chaoran Liu, Ying Zhou, Guowen Xu, Yan Yang, Zhiheng Li, and Yiqiu Lu

Concrete beam-column joints are critical elements in the seismic performance of reinforced concrete (RC) structures. The use of carbon fiber-reinforced polymer (CFRP) reinforcement in these joints has gained attention due to its superior mechanical properties and corrosion resistance. This paper presents a comprehensive study of the seismic performance of CFRP-reinforced concrete beam-column joints, focusing on the development of a suitable formula for estimating the seismic

shear capacity. Utilizing a finite element analysis (FEA) that was both developed and validated using pre-existing test data, a comprehensive parametric study was undertaken to explore the impact of several factors. These factors encompassed axial load, longitudinal reinforcement ratio, and transverse reinforcement ratio, and their effects on the seismic performance of CFRP-RC joints were thoroughly investigated. Eventually, a suitable formula was proposed for estimating the seismic shear capacity of CFRP-RC joints. Research results will lead in a better understanding of the seismic behavior of CFRP-reinforced concrete beam-column joints, which will consequently guide the design and analysis of CFRP-reinforced concrete structures for enhanced seismic performance.

Evaluation of ACI 440.11 Shear Strength Provisions for Members without Stirrups

Stephanie L. Walkup, Eric S. Musselman, Shawn P. Gross, and Hannah Kalamarides

Recently codified language in ACI CODE-440.11-22 provides an equation for concrete shear capacity and imposes a lower bound on this calculation. An experimental study consisting of 39 flexural members without shear reinforcement and tested to failure in shear was used to evaluate the current code provisions, including, most specifically, the lower bound. Comparison of experimental and analytical shear capacities demonstrates that the current code provisions are conservative. More lightly reinforced specimens have a higher variability in experimental-to-nominal concrete shear strength than more heavily reinforced specimens, and this variability appears to be dominated by the depth between the elastic cracked section neutral axis and the depth of the tensile reinforcement, which is the area where aggregate interlock occurs. Based on a comparative reliability study, the lower bound, kcr = 0.16 (5kcr = 0.8), in the code, causes more lightly reinforced specimens (kcr < 0.16) to have lower factors of safety against shear failure than more heavily reinforced specimens (kcr > 0.16). Rather than imposing a lower bound of 5kcr on the current shear strength equation, it would be more prudent to resolve the overprediction of the equation for all specimens.

Fatigue Performance of Real-Scale Precast GFRP Reinforced Lightweight Concrete Arches

Bartosz Piątek and Tomasz Siwowski

Due to a dynamic development of infrastructure, engineers around the world are looking for new materials and structural solutions, which could be more durable, cheaper in the life cycle management, and built quickly. One of prospective solutions for building small-span bridges can be precast lightweight concrete reinforced with glass fiber-reinforced polymer (GFRP) rebars. Thanks to prefabrication, it is possible to shorten the construction time. Using lightweight concrete affects structure weight as well as transportation costs. GFRP rebars can make the structure more durable and also cheaper in terms of life cycle management costs. The paper focuses on the fatigue performance of a real-scale arch (10.0 m (33 ft) long, 1.0 m (3.3 ft) wide, and 2.4 m (7.9 ft) high) made of lightweight concrete and GFRP rebars (LWC/GFRP) in comparison with an arch made of normal weight concrete and typical steel reinforcement (NWC/steel). The fatigue loads ranging from 12 to 120 kN (2.7 to 27 kip) were applied in a sinusoidal variable manner with a frequency of 1.5 Hz. This research revealed that the NWC/steel arch exhibited significantly better fatigue resistance when compared to the LWC/GFRP arch. Differences in the behavior of the NWC/steel and LWC/GFRP models under fatigue load were visible from the beginning of the research. The LWC/GFRP model was exposed to fatigue loads, resulting in gradual deterioration at an early stage. This degradation was evident through stiffness being progressively reduced, leading to increased displacements and strains as the number of load cycles increased. The model did not withstand the fatigue load and was destroyed after approximately 390 thousand load cycles, in contrast to the NWC/steel model, which withstood all 2 million load cycles without significant damages or the stiffness being decreased. However, the prefabricated lightweight concrete arches with composite reinforcement seem to be an interesting alternative of load-bearing elements in infrastructure construction.

Evaluation the Predicted Shear Strength of Concrete Deep Beams Reinforced with FRP Bars

Eklas Hatto Hashim and Hassan Falah Hassan

One of the typical and significant components of big structural superstructures, such as offshore structures, bridges, and large multistory buildings, is the reinforced concrete deep beam. It is mostly used to transfer load foundations, girders, bending and pile caps, and some walls. Numerous research and studies have been done on the behavior of deep beams under stresses because of the significance of deep beams. Even while there are specifications for FRP reinforced deep beam in some codes, along with suggestions for the method prediction of load failure, strut-tie method (STM) method, which is included in most codes, it should be noted that many researches are still reevaluating the factors utilized in the analysis method. This paper offers deep beam analysis methods of the shear models put forth by the codes and some research for many published research samples. The survey database of (120) FRP reinforced deep beams tested in shear was used to conduct the study. All specimens simply supported beam under three or four point load and rectangular cross section. The specimens use included variables web shear reinforcement (horizontal and vertical), compressive strength, shear span to depth ratio (a/d), fiber volume fraction. Models combining steel and FRP reinforcement were excluded. The model evaluated in this study is either unsafe or inaccurate. There is no recommended method for calculating the effect of fiber volume fraction. In this study, an equation is proposed to calculate ultimate shear strength for FRP RC deep beam with and without web reinforcement and use the database to evaluate it.

Convertible Bond Test Apparatus for EB FRP, NSM FRP, FRCM, and Allied Systems: Proof of Concept

Faisal Mukhtar

The first phase of this work uses experimental evidence to critique some shortcomings of the so-called improved double-lap bond shear tests regarding their limited application to wet layup fiber-reinforced polymer (FRP) and their inapplicability to pultruded FRP laminates. Even in the case of the wet layup FRP, the study provides some evidence of high chances of obtaining undesirable fiber rupture that preclude the use of the results as reliable means for interpreting the FRP-concrete bond-slip models. Further proposed modifications to overcome these challenges are provided by designing a convertible bond tester applicable to both wet layup and pultruded FRP laminates. Apart from the application of the apparatus to FRP-concrete bond assessment under pure double shear, it proved to be applicable to conducting mixed-mode bond tests. The second phase of the work upgrades the so-designed test apparatus to make it convertible to bond testing of other variants (near-surface mounted [NSM] FRP bars/strips, fiber-reinforced cementitious mortar [FRCM], etc.) of strengthening systems without developing a different apparatus for each. The apparatus allows testing the NSM FRP-concrete bond in a novel manner compared to the traditional practice. Also, given the absence of mixed-mode studies for FRCM, the apparatus provides a pioneer means of conducting the same.

Flexural behavior of Concrete Beams Prestressed with Hybrid Tendons

Adi Obeidah and Hani Nassif

Developments in the prestressed concrete industry evolved to incorporate innovative design materials and strategies driven towards a more sustainable and durable infrastructure. With steel corrosion being the biggest durability issue for concrete bridges, FRP tendons have been gaining acceptance in modern prestressed technologies, as bonded or unbonded reinforcement, or as part of a "hybrid" system that combines unbonded CFRP tendons and bonded steel strands. Assessments of the efficacy of hybrid-steel beams, combining bonded and unbonded steel tendons. in the construction of segmental bridges and in retrofitting damaged members has been established by several researchers. However, limited research has been conducted on comparable hybrid prestressed beams combining CFRP and steel tendons (hybrid steel-CFRP beams). This paper provides an insight on the flexural behavior of eighteen prestressed beams tested under third-point loading until failure with the emphasis on the tendon materials (i.e., CFRP and steel) and bonding condition (i.e., bonded, unbonded). In addition, a comprehensive finite element analysis of the beams' overall behaviour following the trussed-beam methodology is conducted and compared with the experimental results. Results show that hybrid beams, utilizing CFRP as the unbonded element maintained comparable performance when compared to hybrid steel beams. The results presented in this paper aim to expand the use of hybrid tendons and facilitate their incorporation into standard design provisions and guidelines.

Development of ASCE41 m-Factors for FRP Strengthened Columns

Pedro F. Silva and Tarek Alkhrdaji

This research investigates the performance of rectangular reinforced concrete (RC) columns wrapped with fiber-reinforced polymers (FRP). Design deficiencies have included lap splices of the column longitudinal reinforcement within plastic hinge regions, and widely spaced column ties, which provide modest concrete confinement and poor shear strength. ACI 440 seismic design guidelines for FRP strengthening of plastic hinge regions in RC columns was used in evaluating the lap splice capacity, confinement of concrete in plastic hinge regions and shear strengthening of RC members with FRP. Test results were subsequently used in calibrating and validating an analytical model for use in the software platform OpenSees. This analytical model captured the cyclic inelastic response of RC columns built with insufficient lap splice and transverse reinforcement and retrofitted with FRP composites. Experimental and analytical test results were than used in establishing ASCE 41-17 acceptance criteria for linear and nonlinear design procedures of RC columns wrapped with FRP. Research findings are of interest to a broad range of the engineering community dealing with strengthening of concrete members with FRP. The findings and recommendations can also support further refinement of the ACI 440 seismic design guidelines within the framework of ASCE 41-17.

Biaxial Interaction Diagrams of Elliptical Concrete Column Sections Reinforced with GFRP Bars

Ahmad Ghadban and Hayder A. Rasheed

The release of ACI 440.11-22 building design code for concrete structures reinforced with GFRP bars comes with several challenges at various fronts. One such challenge is tackled in this paper which is the development of limit interaction diagrams for elliptical bridge columns reinforced with GFRP bars under biaxial bending plus axial compression/tension. This type of columns requires special considerations at all levels. This paper depicts the various formulations encountered herein in a detailed treatment highlighting the critical steps to build an efficient analysis algorithm. The formulation is implemented into a user-friendly software developed using object-oriented programming, namely the C# programming language. The robustness of the formulation is tested by comparing interaction diagrams of elliptical sections to those of corresponding rectangular sections. The significance of an ACI code comment requiring bar orientation being considered for circular sections with less than 8 bars is also examined in this paper. This paper also tests the ACI recommendation to neglect GFRP action in compression. Results indicate reasonable similarity among interaction diagrams of elliptical and rectangular sections leading to the conclusion that the formulation presented herein provides an accurate tool to analyze elliptical sections.

Out of plane Strengthening of Masonry Walls with Inorganic Composites

Marta Del Zoppo, Marco Di Ludovico, Alberto Balsamo, and Andrea Prota

Unreinforced masonry buildings (URM) are particularly vulnerable to local out-of-plane failure mechanisms of the walls during earthquakes. This study investigates the effectiveness of a relatively novel class of inorganic composite materials, namely Fiber Reinforced Mortars (FRM), for the out-of-plane strengthening of masonry walls. Experimental tests by using a setup to perform out-of-plane tests on masonry panels, part of an enlarged ongoing testing campaign, are presented herein. Two types of masonry walls are investigated: solid clay brick masonry walls and tuff masonry walls. The specimens are subjected to compressive axial load and out-of-plane horizontal actions according to a "four-point bending test" scheme. Two specimens are reinforced before testing with FRM in double-side configuration, while other two specimens are tested in their bare configuration. Experimental results in terms of capacity curves and deformed shapes are reported and discussed. The preliminary results attest that FRMs are effective in increasing the out-of-plane capacity of masonry walls and in postponing the activation of the out-of-plane failure mechanism.

Numerical Investigation and Experimental Plan on Seismic Performance of Carbon Fiber-Reinforced Polymer-Reinforced Concrete Columns

Chaoran Liu, Ligang Qi, Ying Zhou, Guowen Xu, Yan Yang, Zhiheng Li, and Yiqiu Lu

Fiber-reinforced polymer-reinforced concrete (FRP-RC) structures have won researchers' attention for decades as a considerable substitute due to their superb mechanical and non-mechanical properties. Despite the promising potential of concrete structures with glass FRP and basalt FRP that were shown by previous research, there are few specifications for the seismic design of FRP-RC structures to date due to limited research data on their seismic behavior. This paper focuses on the seismic performance of concrete columns with carbon fiber-reinforced polymer (CFRP) reinforcement by finite element modeling. The effect of longitudinal reinforcement type and ratio, stirrup spacing, concrete strength and axial load ratio are included in the parametric analysis in VecTor2. Properly designed CFRP-RC columns with good confinement generally reach high load-carrying capacity and deformation level, while high axial load could induce relatively severe damage. To verify these conclusions, seven full-scale columns are under construction and will be tested under combined lateral reversed cyclic loading and constant axial loading.

Flexural Strength and Behavior of Inverted-T Precast Concrete Beam Reinforced with Smooth CFRP Bars

Mohd Basri Che Bakar, Raizal Saifulnaz Muhammad Rashid, and Mohd Saleh Jaafar

This study conducts an experimental investigation on inverted-T precast concrete beams reinforced with smooth CFRP bars. The paper aims to evaluate the performances of precast concrete beam reinforced with smooth CFRP bars in terms the bond behavior between CFRP bars and concrete, serviceability and flexural strength. Altogether, nine specimens of CFRP bars embedded in 150 mm concrete cube were tested by pullout test to ascertain the bond behavior between CFRP bars and concrete. The surface of CFRP bars were treated in different methods in order to improve the bond strength. Later on, three sets of inverted-T precast concrete beams were experimentally tested under flexural test. Generally, the experimental results have indicated that the aspects of behavior between CFRP and steel reinforced beams were comparable before the first crack. However, both CFRP and steel reinforced beams behave in distinct way towards the ultimate load in terms of resisting the applied load, deflections, crack width and crack numbers. The results have also shown that reinforcement ratio affects the ultimate load as well as the deflection of the beams. Besides, higher strain in CFRP bars have been recorded for the beams with lower reinforcement ratio.

Evaluation of the Bond Performance of Concrete-Epoxy Interface Using Segmentation-Based Image Processing Techniques

Abubakar S. Ishaq, Maria M. Lopez, Charles E. Bakis, and Yoseok Jeong

This study evaluates the bond performance of concrete epoxy bonds using an image segmentation-based image processing technique. The Concrete Epoxy Interface (CEI) plays a crucial role in the structural performance of FRP-repaired concrete as it transfers stresses from the concrete to the epoxy. By employing the image segmentation technique, the performance of the CEI is assessed through the ratio of Interfacial Failure (IF) to other failure types, namely cohesive failure in Epoxy (CE) and Cohesive cracks in Concrete (CC). The effects of sustained loading duration on CEI bond performance are quantitatively analyzed using 21 single-lap shear (SLS) specimens and 28 notched 3-Point Bending (3PB) specimens. The findings highlight vital conclusions: CE is the least failure mode in SLS and 3PB specimens. In contrast, CC is the predominant failure mode, indicating the susceptibility of the concrete substrate in FRP-repaired concrete. Moreover, IF generally increases with longer sustained loading durations in 3PB specimens but decreases with increased loading duration in SLS specimens. The study also demonstrates the effectiveness of the image segmentation approach in evaluating CEI performance in 3PB specimens, where color distinguishes epoxy, FRP, and concrete substrate.

Modeling Cyclic Response of CFRP Strengthened Fiber Anchored RC Frame Members to Failure

Salman Alshamrani, Sama Mohammed Saleem, Hayder A. Rasheed, and Fahed H. Salahat

There is a shortage of studies related to the effects of fiber anchorage on the behavior of strengthened frame members undergoing seismicity. This study models experimental data of four frame specimens having seismic code-compliant joints with CFRP-strengthened members secured with different fiber anchorage systems.

Analytical formulation using a trilinear moment-curvature response is extended to accurately model the envelope curves of the vertical frame member by including the nonlinear interaction from the horizontal member, which presents a new solution. Furthermore, the experimental hysteresis data provides a basis to formulate an analytical model based on phenomenological observations to capture the cyclic load-drift curves. When modelling the drift-based hysteresis loops, each cycle is divided into three linear regions in the unloading and reloading paths, respectively. These are named push-bound, inflection range, and pull-bound regions. Curves correlating the ratio of unloading and reloading slopes of these regions to the initial backbone curve slope as a function of the drift ratio to yielding drift ratio are generated. These curves define the rules that the hysteresis loops behave according to. The hysteresis rules are calibrated against two different RC frame assemblies and used to predict the cyclic response of two other frame assemblies with similar features.

Physical and Mechanical Properties of Helical Wrap GFRP Bars for Reinforcing Concrete Structures

Girish Narayan Prajapati, Shehab Mehany, Wenxue Chen, and Brahim Benmokrane

This paper presents an experimental study that investigated the physical and mechanical properties of the helical wrap glass fiber-reinforced polymer (GFRP) bars. The physical tests are conducted to check the feasibility and quality of the production process through the cross-sectional area and evaluation of the fiber content, moisture absorption, and glass transition temperature of the specimens. While the mechanical tests in this study included testing of the GFRP specimens to determine their tensile properties, transverse shear, and bond strength. Four bar sizes (#3, #4, #5, and #6), representing the range of GFRP reinforcing bars used in practice as longitudinal reinforcement in concrete members subjected to bending, are selected in this investigation. The GFRP bars had a helical wrap surface. The tensile failure of the GFRP bars started with rupture of glass fibers followed by interlaminar delamination and bar crushing. The bond strength of the GFRP bars satisfied the limits in ASTM D7957/D7957M. The test results reveal that the helical wrap GFRP bars had physical and mechanical properties within the standard limits.

Seismic Strengthening of RC Beam-Column Joints with FRP Systems Applicable from the Exterior of the Building

Ciro Del Vecchio, Marco Di Ludovico, Alberto Balsamo, and Andrea Prota

Recent seismic events demonstrated the high vulnerability of existing reinforced concrete (RC) buildings. Lack of proper seismic details resulted in significant damage to structural components with many collapses and number of fatalities. The destruction of entire cities shield lights on the need of effective strengthening solutions that can be applicable at metropolitan/regional scale. They should be effective increasing significantly the seismic performance, affordable in the cost, fast to apply and with a low level of disruption to the occupants. This research work presents and discusses the preliminary results of an experimental programme on full-scale RC beam-column joints with reinforcement details typical of the existing buildings in the Mediterranean area. After assessing the response of the as-built specimen under a constant axial load and increasing cyclic displacement, a novel FRP-based strengthening system is presented. It combines the use of a quadriaxial CFRP fabric applied on the joint panel with CFRP spikes installed at the end of the beam and columns to improve the bond. The preliminary results pointed out the effectives of this strengthening solution in avoiding the joint panel shear failure and promoting a more ductile failure mode.

Interface Shear Transfer Mechanism with GFRP Bars Reinforcement

Camilo Vega, Abdeldjelil Belarbi, and Antonio Nanni

Most of the research related to interface shear transfer in concrete elements has utilized steel bars as reinforcement, while GFRP reinforcement has received little attention experimentally and analytically. For this reason, only a few design specifications include provisions for the calculation of the interface shear transfer when using GFRP. In this project, an experimental campaign is being conducted to determine the contribution of GFRP bars to the mechanism of shear transfer by using push-off specimens. The literature review and the test methodology are reported in this paper. The obtained results indicate that the use of GFRP reinforcement significantly enhances the interface shear strength, resulting in a capacity that exceeds those of the specimens without reinforcement. When the GFRP-reinforced specimen reaches the first crack at a load similar to that of the unreinforced specimens, it continues carrying load until it reaches a peak, thus indicating that the reinforcement is providing both dowel action and clamping force prior the shear failure. Additionally, once the peak strength is reached, the use of GFRP reinforcement allows the specimen to deform in a pseudo-ductile fashion thus preventing sudden failure.

Shear Behavior of 60-Year-Old Bridge Girder Strengthened Using CFRP Sheets

Mohamed Ahmed, Slimane Metiche, Radhouane Masmoudi, Richard Gagne, and Jean- Philippe Charron

This paper presents preliminary experimental and numerical results of a research program aimed at investigating the residual capacity of 60-year-old reinforced concrete bridge girders strengthened using CFRP sheets. Two 4.5 m and 5.0 m long, bridge girders were deconstructed from a bridge located in Canada. The two 60-year-old girders have been strengthened with CFRP for the last six years of the service life of the bridge. The two full-scale girders were tested at the structural lab of Sherbrooke's University after having suffered under real service conditions. A finite element model using the ANSYS program had been validated with the experimental results before it was used as a control sample for non-strengthened conditions. The test results revealed that the CFRP strengthening technique can extend the service life of the bridge element by keeping their shear capacity safe. The CFRP strengthening configuration of the two girders increased the maximum *shear capacity by 35.5 % and 30 % over the finite element control model. The presented outcomes show the effectiveness of using the external CFRP sheets as an external technique for bridge rehabilitation. The test results were compared with the ACI 440 2R-17 and CSA S6-19 design guidelines. The theoretical comparison between guidelines, experimental and numerical results shows that the two guidelines are considered overly conservative.*

Analysis of Concrete Deep Beams with Fibre-Reinforced Polymer (FRP) Bars by Indeterminate Strut-and-Tie (IST) Method

Shuqing Liu and Maria Anna Polak

This paper presents an indeterminate strut-and-tie (IST) method to analyze concrete deep members reinforced with fibre-reinforced polymer (FRP) bars. Because FRP bars are linear-elastic and brittle at failure, the classical ST method based on steel yielding cannot be used to analyze FRP-reinforced concrete deep beams, and current code provisions lack guidance on such designs. Thus, the IST method is proposed for the analysis. This work addresses the details of using the proposed IST method to analyze FRP-reinforced concrete deep beams, including how to size the struts and nodes without assuming steel yielding, how to model the compressive behaviour of concrete struts reasonably, and how to construct and analyze statically indeterminate ST models. Six FRP-reinforced concrete deep beams with stirrups and six beams without stirrups are analyzed in this work, and it is found that the proposed method works well to predict the shear strength of FRP-reinforced concrete deep beams by comparing the analytical results with the test results.

Fatigue Behavior of CFRP Sheets Attached to Concrete Surface by Using EBROG Strengthening Method

Mehdi Khorasani, Giovanni Muciaccia, and Davood Mostofinejad

The externally bonded reinforcement on grooves (EBROG) technique has been recently shown to outperform its rival techniques of surface preparation (such as externally bonded reinforcement, EBR) employed to delay the undesirably premature debonding of fiber reinforced polymer (FRP) from the concrete substrate in retrofitted structure. However, the behavior of EBROG method under fatigue loading has not been assessed yet, and the present study is the first attempt to achieve the above aim. For this purpose, an experimental program is conducted in which 16 CFRP-to-concrete bonded joints on the concrete slab prepared through the EBROG and EBR techniques are subjected to the single lap-shear test and fatigue cyclic loading. Furthermore, the bond behavior of CFRP strips-to-concrete substrate is investigated in this research in terms of the load capacity, slip, debonding mechanism, and fatigue life. The results showed that the grooving method improved the bond properties of CFRP-to-concrete joints under fatigue loading. By using this alternative technique, the number of cycles until failure (fatigue life) increases incredibly under the same fatigue cycle loading and the service life of strengthened members could be improved under fatigue loading. Furthermore, the effects of different loading levels on the behavior of CFRP-concrete joints installed by EBROG method are evaluated. The results showed that fatigue life of strengthened specimens decreases by increasing fatigue upper load limit. Finally, a new predictive equation was developed based on plotting the maximum applied fatigue load versus fatigue life curves for CFRP-to-concrete bonded joints for the EBROG method.

Effect of Weathering Exposure Time on the Flexural Behavior of FRP Strengthened RC Beams

Haitham A. Ibrahim, Mohamed F. M. Fahmy, and Seyed Saman Khedmatgozar Dolati

This study numerically investigates the long-term effectiveness of using externally bonded fiber-reinforced polymer (FRP) plates as a strengthening technique for reinforced concrete (RC) beams. A two-dimensional finite element model (FEM) that can accurately predict the flexural behavior of FRP strengthened RC beams, is developed. Weathering exposure time of 0.0, 15.5, 35, and 75 years were considered. In total, 28 different concrete beams were modelled using the developed FEM. The results show that prolonged exposure to natural weathering can cause premature FRP debonding, even before reaching the yielding load. The ultimate load capacity, midspan deflection, and ductility of strengthened RC beams can be reduced by up to 38%, 62%, and 100%, respectively. In addition, the findings raised concerns about the applicability of the ACI 440.2R-17 provisions for calculating the design flexural strength of FRP strengthened RC beams with prolonged exposure to natural weathering. To ensure a safe design for strengthened beams with FRP debonding or concrete crushing failure modes, this paper recommends an additional reduction factor ranging from 0.8 to 0.9. Furthermore, periodic inspection using non-destructive testing and FRP anchorage system are highly recommended for both existing and new applications of FRP in structures.

An Effective Simple Fixture for Testing GFRP Rebars in Compression

Alireza Sadat Hosseini and Pedram Sadeghian

The compressive strength of glass fiber-reinforced polymer (GFRP) rebars is investigated and a new test method is proposed. The program consists of three test series. In Test Series 1, the strengths and weaknesses of the test methodology outlined in ASTM D695-15 were explored. Specimens with varying length-to-diameter ratios were prepared and tested. Premature failure was observed, and longitudinal splitting was the dominant failure mode. Test Series 2 aimed to prevent failure initiation at the ends by using steel clamps. The clamps confined the specimen ends and prevented failure propagation. The compressive strengths showed an average of around 70% the tensile strength. In Test Series 3, an advanced fixture was designed to overcome the limitations of the previous series by including clamping parts and vertical steel bars. Three different loading speeds were employed, and an average compressive strength of 75% of the tensile strength was found. The tests were followed by a statistical analysis indicating a significant difference between the results of the three test methods. The proposed test

method offers a practical and reusable approach for evaluating the compressive strength of GFRP rebars. However, further analysis is recommended for a more comprehensive understanding of the compressive behavior of these rebars.

Stress-strain Model of Concrete Confined by FRP Laminate and Spike Anchors

Zhibin Li, Enrique del Rey Castillo, Richard S. Henry, Kent A. Harries, and Tongyue Zhang

The application of fiber-reinforced polymer (FRP) jacketing for confinement may not always be feasible, particularly in cases where adjacent elements obstruct the structural member and prevent wrapping. To address this issue, the utilization of FRP laminate and spike anchors has been proven as an alternative solution. This study focuses on proposing a design methodology for this particular application. A stress-strain model was developed to assess the behavior of concrete prisms confined with FRP laminates and spike anchors under axial compression. The model adopts a bi-parabola stress-strain curve, with the coefficients derived from previously published experimental data on concrete prisms confined using this solution. The comparison between the analytical and tested stress-strain curves yielded a coefficient of determination (R2) averaging at 0.96, demonstrating the effectiveness of the bi-parabola model in describing the tested stress-strain responses.

Finite Element Analysis of the Interface between FRP and Concrete

Todor Zhelyazov, Eythor Rafn Thorhallsson, and Jonas Thor Snaebjornsson

The study delves into modeling the interface between Fiber-Reinforced Polymer (FRP) and concrete, with a specific emphasis on simulating the gradual deterioration of bond strength. A model rooted in continuum damage mechanics is integrated with an empirically derived relationship to address interfacial shear failure. Material models are defined for the concrete, the externally bonded FRP reinforcement, and the adhesive layer. These material models are implemented in finite element simulations, replicating experimental setups widely used to investigate the FRP-concrete interface. Key results are reported and discussed. More precisely, the numerically obtained load-slip relationships for the interface and visualizations of the damaged zones in concrete are provided. The numerical results are in close agreement with existing experimental data. The finite element analyses suggest that concrete degradation is not limited to the areas near the adhesive joint. This implies that the adhesive joint could influence the overall behavior of the structural elements, even when debonding failures are prevented by anchorage devices.

Experimental Assessment of Large-Scale FRP-Strengthened RC Shear Controlled Walls Subjected to Cyclic Loads

Sheng-Hsuan Lin, Insung Kim, Ravindra Kanitkar, Garrett R. Hagen, Griffith L. Shapack, and Aniket D. Borwankar

Fiber reinforced polymers (FRP) are commonly used to seismically retrofit concrete structural walls. Limited design guidance for the seismic application of FRP strengthening is currently available to designers in guidelines such as ACI PRC-440.2-17 or standards like ASCE/SEI 41-17. This paper presents the description and results of an experimental effort to investigate the effectiveness of FRP retrofitted concrete walls. The specimen wall thickness was either 6 in or 12 in, which represents a typical range of wall thickness seen in older buildings. To better reflect the most common applications seen in the industry, the walls were retrofitted with FRP, and anchored with fiber anchors only on one side of the wall. The study demonstrates that the effectiveness of FRP is reduced as the wall thickness increases and that the FRP must be anchored to the wall for any tangible benefit. The results are used to assess the current provisions in ACI PRC-440.2-17 and ASCE/SEI 41-17. It is apparent that additional testing is required to better understand the complexities involved in the FRP strengthening of shear walls and such testing is scheduled for the near future.

Discontinuous FRCM-confinement of Masonry Columns

Alessio Cascardi, Salvatore Verre, and Luciano Ombres

This paper presents an experimental study on the discontinuous confinement of small-scale masonry columns using a FRCM system. The study aims to investigate the effectiveness of the FRCM in enhancing compressive strength and ductility under axial loading condition. In detail, the adopted FRCM system was composed of a cementitious matrix reinforced with PBO mesh. It was applied to the masonry columns using a discontinuous wrapping technique, which involved wrapping the FRCM material around the column in segments, leaving gaps between the segments itself. More in deep, the experimental program included twelve specimens, ten (i.e. five couples) of which were wrapped with the PBO-FRCM system using the discontinuous wrapping technique, while the remaining two columns were left unconfined and served as the control group. The columns were measured concerning the load-displacement behavior, ultimate strength and failure mode and then compared between the FRCM-confined and unconfined columns. In particular, the amount of fiber in the vertical direction was kept constant, while the scheme of confinement was varied by both changing the strip width and spacing. In total, five different schemes of discontinuous confinement were proved. The performed research aims to contribute to the knowledge in the field of FRCM-masonry confinement, mainly focusing on the influence of the mentioned parameter.

Open Issues on the Structural Performances of Concrete Beams Reinforced with FRP (Fiber Reinforced Polymers) Rebars

Maria Antonietta Aiello and Luciano Ombres

The issues related to deformability, strength and ductility of concrete elements reinforced with FRP (Fiber Reinforced Polymer) bars are critically analyzed and discussed in this paper. The analysis is conducted from an experimental point of view by means of bending tests on concrete beams reinforced with Carbon FRP (CFRP) bars with different amounts of reinforcement, and by an analytical approach aiming to evaluate the deflection and cracking phenomenon (number and width of cracks). The experimental results are compared with the analytical predictions and with predictions developed on the basis of the available codes (ACI, EC2, JSCE). The analysis of the results obtained confirms the most relevant issues of the mechanical behavior of FRP bar-reinforced beams, still worthy of research efforts; some technological and construction solutions that can provide significant improvements are also addressed..

Behavior of Partially Bonded GFRP-Reinforced Concrete Beams

Ali Alatify and Yail J. Kim

The serviceability and ultimate limit states of a concrete member are reliant upon the bond of reinforcement. The performance of glass fiber reinforced polymer (GFRP) reinforced concrete structures is influenced by multiple parameters and one of these parameters is the bond length of GFRP rebars. The scope of the present research is to experimentally study the effects of fully and partially bonded rebars on the load-bearing capacity and cracking of GFRP-reinforced concrete beams. The beams with partially bonded reinforcement show reduced capacities compared with those with fully bonded reinforcement, and the former reveals localized cracks. The partially bonded beams fail as a result of concrete splitting, while their fully bonded counterparts fail by concrete crushing.

Bond Performance of CFRP-Concrete Joints Subjected to Freeze-Thaw Cycles: Experimental Study and Analytical Analysis

Ahmed Kallel, Radhouane Masmoudi, Benoit Bissonnette, and Marcelin Joanis

The durability of the bond between carbon fiber reinforced polymer (CFRP) and concrete surface under freeze-thaw (FT) cycles is a very significant issue in the application of external CFRP strengthening of reinforced concrete structures. This paper presents an experimental and analytical study on the bond behavior between CFRP and concrete under FT cycles. In this study, the samples were exposed to freeze-thaw cycles in accordance with ASTM C666 where the temperature range varies between -18 °C to +4 °C. Moreover, the bond properties between CFRP and concrete were experimentally evaluated through single lap shear tests and compared with the analytical prediction models proposed in the literature. The failure modes of the control samples as well as the samples exposed to freeze-thaw cycles were presented in this research. In addition, the load-slip behavior was discussed. A non-linear bond-slip relationship between the CFRP-concrete interface was presented at 0, 100, 200, and 300 of freeze-thaw cycles. The results show that the cohesive failure of concrete substrate was observed for the control samples. On the other hand, the mode of the interface failure was changed after exposure to freeze-thaw cycles. In addition, the bond strength of the CFRP-concrete interface increases with increasing freeze-thaw cycles.

Durability of a Solid Slab Bridge with Overlays Incorporating BFRP Grids

Jun Wang and Yail J. Kim

When reinforced concrete is exposed to a corrosive environment with sufficient moisture and oxygen, 5 chloride ions may penetrate the concrete and result in the corrosion of reinforcement. Overlays are frequently placed 6 to protect the superstructure of a bridge, thereby extending its service life. Through advanced simulation techniques, 7 this research studies the durability of a solid slab bridge overlaid with ordinary concrete and high performance concrete 8 (HPC) alongside basalt fiber reinforced polymer (BFRP) grids. A computer program called Virtual Cement and 9 Concrete Testing Laboratory (VCCTL) is adopted to model the three-dimensional microstructure of the overlays; 10 afterward, agent-based modeling is conducted to examine the random migration of chloride ions. After the migration 11 of chlorides is simulated, the time-dependent response of the overlaid solid slab with the BFRP grids is evaluated.

Failure Characterization of GFRP-Reinforced Concrete Walls

Ju-Hyung Kim and Yail J. Kim

This paper presents a new methodology for characterizing the failure mode of structural walls reinforced with glass fiber reinforced polymer (GFRP) bars. An analytical model is used to derive a non-dimensional failure determinant function, which is validated against existing test results. The function involves geometric attributes (wall length, wall height, and boundary element size), reinforcement ratios (horizontal and vertical), and material properties (compressive strength of concrete and tensile strength of GFRP bars). According to the determinant function, structural walls fail in flexure when a high aspect ratio is associated with a relatively low reinforcement ratio in the boundary element. The proposed methodology and design recommendations provide valuable guidance for practitioners dealing with GFRP-reinforced concrete walls.

Assessment of the Existing Shear Resistance Models for RC Beams Strengthened with Near Surface-Mounted FRP Reinforcement

Amirhossein Mohammadi, Joaquim A.O. Barros, José Sena-Cruz, and Salvador J.E. Dias

The near surface-mounted (NSM) technique utilizing fibre-reinforced polymer (FRP) reinforcements has gained significant popularity in enhancing the shear resistance of reinforced concrete (RC) beams. Various models have been proposed to predict the shear contribution of NSM FRP reinforcement in RC beams. In this study, the performance of five well-established models, namely those proposed by De Lorenzis and Nanni, Rizzo and De Lorenzis, Dias and Barros, Bianco et al., and Mofidi et al., is assessed. A comprehensive database comprising 137 beams from published works is compiled for this assessment. The findings reveal that the model proposed by Bianco et al. exhibits superior predictive performance but tends to produce extremely conservative predictions. On the other hand, the model proposed by Dias and Barros performs well for beams shear strengthened with FRP laminates, although it is not specifically calibrated for specimens shear strengthened with FRP rods. Notably, the latter model results within an appropriate safety domain, avoiding extreme conservatism. Further research is warranted to develop a comprehensive model with enhanced predictive accuracy.

Bond-Deteriorated Reinforcement Concrete Beams Strengthened with CFRP

Riliang Li and Riyad S Aboutaha

Reinforcement corrosion is one of the most commonly occurring problems that negatively affect the performance of reinforced concrete (RC) structures. For RC beams, corrosion of reinforcement often leads to deterioration of bond between main tensile reinforcement and concrete. There are many ways to rehabilitate bond-deteriorated RC beams. Techniques utilizing carbon fiber reinforced polymers (CFRP) are often adopted due to its properties of lightweight, high strength and corrosion resistance. The objective of this study is to examine the effect of CFRP on the performance of bond-deteriorated RC beams using the finite element analysis (FEA) software ABAQUS to simulate the actual experiment. The results show that the unbonded length of main tensile reinforcement and the thickness of CFRP have a significant effect on the ultimate flexural strength of RC beams. Although the increasing of unbonded length reduce the ultimate load and stiffness of RC beams, using CFRP at the bottom contributes markedly to increasing ultimate load and stiffness of bond-deteriorated RC beams. These simulation results will play an important role in the future research of CFRP strengthening technology.

A Review of Strut-and-Tie Models for FRP Reinforced Deep Beams

Taylor J. Brodbeck, Giorgio T. Proestos, and Rudolf Seracino

This paper presents the current code provisions on strut-and-tie analysis and design of disturbed regions of deep concrete beams reinforced with fiber-reinforced polymer reinforcing (FRP) bars. A literature review of the large-scale experiments published to date is included with a comparison of their results to strut-and-tie predictions. Several published works have recommended modifications to strut-and-tie provisions for FRP reinforced deep beams, and those modifications are summarized within this paper.

A Novel VOC-Free Epoxy System for High Modulus Glass Fiber Reinforced Polymer Rebar

Huifeng Qian and Wendell Harriman II

Fiber reinforced polymer (FRP) composite rebar is a non-metallic concrete reinforcement alternative that has been successfully deployed in hundreds of structural applications globally. The increasing demand for FRP rebar as a metal alternative is driven by its unique value proposition, including lightweight, high strength, magnetic transparency, and most significantly, corrosion resistance. FRP rebar is fabricated through pultrusion, a high throughput composite fabrication process in which, resin-impregnated fiber undergoes rapid cure when pulled through a heated furnace. Considering the open nature of the open pultrusion process, expansion of production capacity for FRP rebar manufacturing demands the use of advanced resins that are free from Volatile Organic Compounds (VOCs), enable high throughput production, and deliver an outstanding translation of fiber properties following cure. In this work, we will present an epoxy system that is inherently VOC Free and is tailored to enable high throughput manufacturing of glass fiber reinforced polymer (GFRP) rebar at scale. Furthermore, the rapid formation of highly crosslinked structures achieved with this resin system during pultrusion is found to enable outstanding fiber property translation resulting in high modulus (>70 GPa) and corrosion resistance (>80 % tensile strength retention without load) that exceeds existing standards such as ASTM D7957.

Data-Driven Prediction of The Bond Coefficient Between Fibre-Reinforced Polymer (FRP) Bars and Concrete

Nadia Nassif, M. Talha Junaid, Salah Altoubat, Mohamed Maalej, and Samer Barakat

Fiber-reinforced polymer (FRP) bars can serve as an appropriate substitute for steel rebar due to their lightweight, high strength, and good corrosion resistance. Nevertheless, the long-term success of FRP bars as promising reinforcement in concrete depends on understanding the bond between FRP bars and concrete. ACI 440.1R-15 recommends utilizing CSA S806-12 Annex S "Test Method for Determining the Bond-Dependent Coefficient of FRP Rods" for estimating the design value of the bond-dependent coefficient (kb). However, this testing method requires a four-point loaded 3.0-meter-long beam with continuous assessment of developed crack width. Due to the complexity of the test, studies were scarce in assessing the factors affecting the kb. Therefore, this study aimed to relate the experimental kb obtained from large-scale testing to a relatively simpler bond strength value, τu , obtained from smaller-scale FRP pull-out test. The relation was

established utilizing data collection for both tests from experimental studies. Three machine learning techniques (Ensembled Trees Artificial Neural Network and Gaussian Process Machines) were then applied to mimic and understand the complex bond-behavior at varying FRP and concrete properties. The results have shown promising relation (R2>0.8) between kb and τu for different surface textures and fiber types.

Model Uncertainty in Reliability Analysis of FRP-To-Concrete Bond with Grooves

Zhao Wang and Baolin Wan

The use of fiber-reinforced polymer (FRP) composites for external bonding has become a popular and widely accepted technique for enhancing the strength of concrete structures due to its excellent mechanical performance, corrosion resistance, and ease of construction. However, premature debonding is a major challenge as it prevents the full capacity of FRP composites from being achieved, resulting in material waste. Recently, grooving the surface of concrete before bonding FRP has emerged as a potential solution to this problem. Several experimental studies have evaluated the bond strength of FRP-to-concrete joints with grooves. To facilitate the practical application of this technique, it is necessary to develop comprehensive reliability-based design guidelines that account for the uncertainty arising from various aspects such as materials, model errors, and loading. A critical factor of such analysis is the calibration of model uncertainty which significantly affects the accuracy of reliability-based design and analysis. The objective of this study was to measure the model uncertainty of the existing prediction model for FRP-to-concrete joint with a longitudinal groove by involving the model factor which is defined as the ratio of observed values from experimental test to calculated values from prediction models. To eliminate the potential correlation from critical parameters, the residual model factor was isolated from model factor by separating the systematic part. The lognormal distribution was found to be the most suitable distribution function to describe the residual model factor, and the mean and variance were determined. With this newfound knowledge, we are better equipped to account for uncertainties in the design and construction of FRP-to-concrete connections with grooves, which will ultimately result in more durable and reliable structural improvements.

A Comparative Analysis of GFRP- and Steel-RC Columns under Combined Shear, Flexure, and Torsion Loads

Yasser M. Selmy and Ehab F. El-Salakawy

The seismic performance of reinforced concrete (RC) bridge columns subjected to multidirectional ground motions is a critical issue, as these columns can experience axial compression, bending, and torsional loading. Moreover, steel corrosion is a significant concern in existing bridges, leading to deficiencies in steel-RC structural members. The use of glass fiber-reinforced polymer (GFRP) reinforcement has been established as a practical and effective solution to mitigate the corrosion-related issues associated with traditional steel reinforcement in concrete structures. However, the dissimilar mechanical properties of GFRP and steel have raised apprehensions regarding its feasibility in seismic-resistant structures. The current study involves conducting an experimental investigation to assess the feasibility of utilizing GFRP reinforcement as a substitute for conventional steel reinforcement in circular RC bridge columns subjected to cyclic lateral loading, which induces shear, bending, and torsion. One column was reinforced with GFRP bars and stirrups, while the other column, served as a control and was reinforced with conventional steel reinforcement. The aim of this investigation was to analyze the lateral displacement deformability and energy dissipation characteristics of the GFRP-RC column. The results showed that GFRP-RC column exhibited stable post-peak behavior and high levels of deformability under the applied combined loading. Additionally, with a torsion-to-bending moment ratio of 0.2, both columns reached similar lateral load and torsional moment capacities and were able to attain lateral-drift capacities exceeding the minimum requirements of North American design codes and guidelines.

Exploring Strength of Straight and Bent GFRP Bars: Refinements to CSA S807:19 Annex E

Ahmed Khalil, Rami A. Hawileh, and Mousa Attom

This study explores technological advancements enabling the utilization of GFRP bars in concrete structures, particularly in coastal areas. However, GFRP bars often encounter reduced bend strength at specific bend locations, which may pose a challenge in their practical application. Various properties such as the strength of bent GFRP bars are crucial for quality assurance, yet existing testing methods stated in ASTM D7914M-21 and ACI 440.3R-15 have limitations when applied to different GFRP bent shapes. Furthermore, those methods require special precautions to ensure symmetry and avoid eccentricities in specimens. To address these challenges, CSA S807:19 introduced a simpler standardized testing procedure that involves embedding a single L-shaped GFRP stirrup in a concrete block. However, the specified large block size in CSA S807:19 Annex E may pose difficulties for both laboratory and on-site quality control tests. Therefore, CSA S807:19 Annex E (Clause 7.1.2b) permits the use of a customized block size, as long as it meets the bend strength of the FRP bars without causing concrete splitting. To date, very few prior research has explored the use of custom block sizes. Therefore, this study aims to thoroughly investigate the strength of bent FRP bars with custom block sizes and without block confinement. Such an investigation serves to highlight the user-friendliness and efficiency of the CSA S807:19 Annex E method. The study recommends two block sizes: 200x400x300 mm (7.87x15.75x11.81 in) for bars <16 mm (0.63 in) diameter and 200x200x300 mm (7.87x7.87x11.81 in) for bars <12 mm (0.39 in). Additionally, the study cautions against using confinement reinforcement, especially with smaller blocks, as it could interfere with the embedded bent FRP bar. Furthermore, the study suggests incorporating additional tail length to mitigate the debonding effects resulting from fixing the strain gauges to the bent portion of the embedded FRP bar. By exploring these modifications, the study seeks to enhance the effectiveness of the testing procedure and expand its practical application for both laboratory and on-site quality assurance. The findings hold implications for the reliable testing of GFRP bars' strength, advancing their use as reinforcement in concrete structures.

Fracture Energy of GFRP-Concrete Bonded Interface after Sustained Loading in Natural Environments

Jaeha Lee, Kivanc Artun, Charles E. Bakis, Maria M. Lopez, and Thomas E. Boothby

Small-scale plain concrete precracked beams strengthened with glass fiber reinforced polymer (GFRP) sheets underwent testing in 3-point flexure to assess variations in the FRP-concrete Mode II interfacial fracture energy after 6 and 13 years of sustained loading in indoor and outdoor environments. The Mode II fracture energy of the interfacial region, GF, was determined by analyzing strain profiles along the length of the FRP sheet, which were obtained using digital image correlation and photoelastic techniques. In the experiments conducted after conditioning, higher GF values were observed as the debonded zone progressed from the region of sustained shear stress transfer to the unstressed section of the interfacial region, particularly in beams subjected to outdoor conditioning. In the interfacial region near the notch, GFRP beams showed reductions in GF in both indoor and outdoor environments. For outdoor beams with GFRP sheets, there was no additional degradation in GF when the FRP was exposed to direct sunlight, in comparison to beams with the FRP exposed to indirect sunlight.

Evaluation of Hysteretic Energy and Damping Capacity of GFRP-RC Columns Under Cyclic Loading

Yasser M. Selmy, Amr E. Abdallah, and Ehab F. El-Salakawy

The seismic performance of reinforced concrete (RC) structures relies on their ability to dissipate earthquake-induced energy through hysteric behavior. Ductility, energy dissipation, and viscous damping are commonly used as performance indicators for steel-RC seismic force-resisting systems (SFRSs). However, while several previous studies have proposed energy-based indices to assess energy dissipation and damping of steel-RC SFRSs, there is a lack of research on fiber-reinforced polymer (FRP)-RC structures. This study examines the applicability of the existing energy dissipation and damping models developed for steel-RC columns to glass FRP (GFRP)-RC ones, where the relationships between energy indices and equivalent viscous damping versus displacement ductility were analyzed for GFRP-RC circular columns from the literature. In addition, prediction models were derived to estimate energy dissipation, viscous damping, and stiffness degradation of such types of columns. It was concluded that similar lower limit values for energy-based ductility parameters of steel-RC columns can be applied to GFRP-RC circular columns, whereas the minimum value and analytical models for the equivalent viscous damping ratio developed for steel-RC columns are not applicable. The derived models for energy indices, viscous damping, and stiffness degradation had an R2 factor of up to 0.99, 0.7, and 0.83, respectively. These findings contribute to the development of seismic design provisions for GFRP-RC structures, addressing the limitations in current codes and standards.

Structural and Deformational Behavior of Flexural Concrete Beams Reinforced with GFRP and BFRP Rebars

Raphael Kampmann, Tim Rauert, Niklas Pelka, and Bastian Franzenburg

Corrosion of reinforcement steel is a major issue for many structural concrete components, because it leads to strength reduction and may significantly reduce the service life. For this reason, fiber-reinforced polymer rebars (FRP rebars) have been developed, as they represent a viable alternative that may replace reinforcing steel for structures that are particularly susceptible to corrosion issues. However, structural design philosophies for these new materials are still in development and further research is needed to implement FRP rebars properly and safely in design codes but also to ensure that design calculations properly predict the actual behavior and performance of FRP reinforced structures. This study was conducted to evaluate the strength and structural deformation behavior of flexural beams that were designed according to Eurocode 2 and, for comparison, according to different design methods pro- posed for FRP reinforced structures. With regard to the development of a uniform design concept for alternative reinforcement materials existing in Germany/Europe, different bending design concepts including the serviceability limit state were evaluated. In addition, the theoretically calculated and predicted strength/deformation were compared to the experimentally obtained measurements. A total of 15 flexural beams, with an overall length of 4.5 m (177 in.), a width of 200 mm (7.8 in.), and a height of 400 mm (15.8 in.), were cast; three of these beams (designed according to Eurocode 2) featured traditional steel reinforcement, to serve as control group. The remaining 12 flexural beams were evenly allocated to capture the two alternative reinforcement materials, while generating three different reinforcement distribution patterns with comparable reinforcement ratios (equivalent cross-sectional areas). Thus, a total of six subgroups – three with GFRP and three with BFRP – each with two specimens, were analyzed. To test all beam in pure bending and to eliminate the influence from shear forces, two equally increasing loads were applied at the (longitudinal) third-points of the beams. Both deflections and loads were measured at several points to evaluate the structural performance of the FRP reinforced structural members. The results showed that the deflection of the glass fiber reinforced bars at the design load capacity measured twice as much as the deflection of the control group. Almost three times as much deflection (at the same load) was observed for the concrete beams reinforced with basalt fiber rebars. In addition, it was observed that the concrete beams with glass and basalt fiber reinforcement bars showed a nearly elastic-elastic behavior up to the point of failure, whereas the steel-reinforced concrete beams showed an elastic-plastic behavior. However, the deformational behavior differed between the various beam types. While the prevailing equations properly captured the post-cracking performance of traditionally reinforced concrete beams, they do not adequately predict the deflections of FRP reinforced concrete beams. From the measurements and analyses, it was concluded that the serviceability limit state (SST) is more critical than the ultimate limit state (LTS) for the design of concrete flexural beams reinforced with FRP rebars.

The Performance of Prestressed Carbon Fibre Reinforced Polymer (CFRP) Bridge Tendons after 18 Years in Service

Alexandra Boloux, Luke Bisby, Valentin Ott, and Giovanni P. Terrasi

Carbon Fibre Reinforced Polymers (CFRPs) are a material of choice in the aerospace and automotive industry, but despite decades of research into their application in structural engineering applications, and in particular in new-build construction of buildings and bridges, CFRP elements remain regarded as somewhat exotic in structural engineering and their widespread take-up is mostly limited to the non-prestressed strengthening of conventional structural members. The study presented in this paper assessed the performance of CFRP bridge tendons, prestressed for 18 years at 45% of their design ultimate tensile capacity in a non-conditioned outdoor environment, over water, in Lucerne, Switzerland. The performance of the tendons is considered alongside pristine samples of the same tendons never used and stored, unstressed, indoors since 1997. Thermal characterization (matrix digestion, thermogravimetric analysis (TGA), dynamic mechanical analysis (DMA), differential scanning calorimetry (DSC)) was used to determine the fibre volume fraction and glass transition temperature, and tensile tests were performed and compared against available original baseline results from 1997. These comparisons show that the in-service tendons do not appear to have been adversely affected by 18 years of service under sustained loading, and have retained the vast majority of their original, unstressed material properties. The in-service tendons only lost about 10.5% of their ultimate tensile capacity over time, while the pristine (unstressed) tendons also lost 7.9% of their capacity; this suggests that sustained loading and an external, unconditioned service environment do not significantly adversely affect the mechanical properties of the tendons after 18 years in service.

Use of CFRP Rebars As Retrofitting System for Masonry Panels

F. Ferretti, A. R. Tilocca, A. Incerti, S. Barattucci, and M. Savoia

In the last decades, the devastating effects of earthquake events in seismic prone regions increased the attention on the vulnerability of existing constructions. Masonry walls especially experienced severe damage, both considering out-of-plane and in-plane mechanisms. To increase their resistance to horizontal forces, different strengthening systems can be applied. The objective of the present work is to study the efficiency of an innovative strengthening solution, involving the use of fiber reinforced polymer (FRP) pultruded bars. An experimental campaign is presented, in which clay-brick single-leaf masonry panels are retrofitted by carbon FRP rebars, inserted into grooves cut within the masonry panel with a cementitious mortar, and CFRP sheets applied on the panel external surfaces. A total of seven direct shear tests (ST) and four diagonal compression tests (DC) were performed on unreinforced and strengthened samples. The results of the tests showed that the strengthening technique can be effective for the improvement of the shear sliding and diagonal cracking resistances, also allowing to deepen the knowledge of the principal failure mechanisms characterizing the FRP-retrofitted masonry elements.

Application of FRP in the Rehabilitation of Prestressed Concrete Girder Bridges

Ramin Rameshni, Reza Sadjadi, and Melanie Knowles.

Deterioration of concrete bridges has resulted in reduction of their service lives and increase in required maintenance which is associated with cost and inconvenience to the public. A prevalent cause of concrete bridge deterioration is corrosion which initiates by chloride ions penetration past the protecting layers and by corroding the steel reinforcement. Because corrosion in prestressed concrete members has more serious consequences than in non-prestressed reinforced concrete, it is important that bridge designers and inspectors be aware of the potential problems and environments that may cause the issue and address them as soon as they are detected. This paper discusses a case study of a highway bridge (Hyndman Bridge, Ontario) including its deterioration, causes, mitigation measures, structural evaluation and the selected repair method. The rehabilitation design is based on guidelines of the latest editions of the CHDBC and ACI 440.2R. CFRP strengthening techniques have been proposed to address the flexure and shear deficient capacity of deteriorated girders. It is concluded that by using a suitable repair methodology employing CFRP, it is possible to upgrade the bridge to comply with the latest requirements of the code and increase the service life of the structure which otherwise would have needed imminent replacement.

Recent FRP Code Developments in the United States for Reinforcing and Strengthening Concrete Structures

Maria Lopez de Murphy

The presentation will set the stage for a panel discussion on recent US developments of codes related to external and internal FRP and their use in concrete structures.

Canadian Codes on FRP and the underlying Research and Field Applications

Shamim Sheikh

The presentation will include a brief update on Canadian codes related to external and internal FRP and their use in structures. A few examples of background research and field applications will also be presented. Some information on seismic resistance of FRP-reinforced concrete structures will also be included.

Design of FRP-reinforced Concrete Structures in Europe

Tommaso D'Antino

The presentation provides an overview of the design procedures currently available in Europe for FRP-reinforced concrete structures. The European fib, Italian CNR, and French AFGC guidelines are considered. FRP reinforcement characterization, as well as bending, shear, and anchorage requirements are discussed.

Recent FRP Code Developments in China for Reinforcing and Strengthening Concrete Structures

Peng Feng

The presentation will set the stage for a panel discussion on recent developments of Chinese codes related to external and internal FRP and their use in concrete structures.

Discussion of FRP Design Codes and Guidelines in Brazil and South America

Daniel Carlos Taissum Cardoso

This presentation will provide an overview on the use of FRP for RC structures in Brazil and South America, along with the current status of codes and guidelines development in the region. The main features of the Brazilian standard will be briefly introduced, with a focus on its original contributions.

Engineering Practices for the use of FRP in Latin America - The Role of the Codes and Guidelines

Gustavo Tumialan

This presentation will provide an overview of engineering practices for the design and construction of FRP systems for existing and new construction in some Latin American countries. The presentation will describe the codes or guides used for FRP design, typically ACI and European documents, and their influence in the local engineering practices.

Sustainable Marine Infrastructure Enabled by the Innovative Use of Seawater Sea-Sand Concrete and Fibre-Reinforced Polymer Composites

Tao Yu and Jin-Guang Teng

Fibre-reinforced polymer (FRP)-reinforced seawater sea-sand concrete (FRP-SSC) structures are an emerging type of structures first proposed by the second author. Built upon the excellent resistance of FRP against various corrosive agents in the marine environment, FRP-SSC structures open up a new horizon for the construction of marine infrastructure by making use of locally available seawater and sea-sand. In addition to their expected excellent durability, FRP-SSC structures offer many compelling advantages, including cost savings in material transportation and reduced mining of river-sand. A major research project led by The Hong Kong Polytechnic University is ongoing, with the aim being to develop innovative forms of, and reliable design methods for FRP-SSC structures to facilitate their wide practical applications. The project covers various aspects ranging from the material level (i.e., SSC, FRP and their interface) to the structural level (i.e., innovative forms and structural behaviour), with a focus on the long-term performance in the marine environment. This presentation will explain the rationale behind FRP-SSC structures and present a summary of the progress of the major project mentioned above, including the results from a large experimental program of field exposure tests involving various types of specimens which have been placed on an exposure site for over three years.

Fatigue Performance under Rolling Load of Full-Scale Concrete Bridge Deck with GFRP Stay-In-Place Form

Amir Fam and Chongxi Gao

A full scale (15.24 m x 3.89 m) reinforced concrete bridge deck supported by steel girders spaced at 3.05 m was built and tested under cyclic rolling load fatigue using a new Rolling Load Simulator (ROLLS) at Queen's University, Canada. The deck included different reinforcement types and materials. One middle section, 3.81 m x 3.89 m was supported by a new design of GFRP stay-in-place structural form system which also served as the bottom reinforcement. The system comprised GFRP I-beams running in the transverse direction (i.e. perpendicular to traffic direction) at 900 mm spacing and supported by the top flanges of the steel girders. Flat GFRP plates with integral T-up ribs were then used to span the spacing between the GFRP I-girders and were supported by their bottom flanges where the T-up ribs ran longitudinally (i.e. parallel to traffic). Epoxy adhesive and self-taping screws were used at the connections. Concrete was then poured where the webs and top flanges of the I-beams as well as the T-up ribs were all embedded inside the deck. A GFRP rebar mesh supported by the top flanges of the I-beams was used as top reinforcement. A total of three million equivalent cycles were completed using two half-axle loads spaced at 1.2 m, applied through the dual tires of the machine as shown in the figure below. Stiffness of the deck was assesses periodically using a quasi-static monotonic loading to establish the slope of the load-deflection curve. This was then used to establish the stiffness degradation over the loading history of the three million cycles.

The Implementation of Fire Resistance Recommendations in ACI Code-440.11

Hamzeh Hajiloo, Mark Green, and Bronwyn Chorlton

Glass fibre reinforced polymer (GFRP) bars are a viable solution for corrosion-prone steel bars in reinforced concrete structures. However, the fire performance of GFRP reinforced concrete has been a major concern due to the degradation of GFRP material properties at high temperatures. The consideration of fire resistance in GFRP reinforced concrete has come a long way from not recommending GFRP internal reinforcement for structures, in which fire resistance is essential to maintain structural integrity, to providing design provisions to achieve the desired fire resistance. The former was from ACI 440.1R (2006) and the latter is from ACI CODE-440.11-22. Canadian standard CSA-S806-12 provides a semi-empirical approach for determining the fire resistance of FRP reinforced concrete slabs based on the minimum concrete cover which is overdue for an update incorporating the recent advances in the field. Several full-scale fire tests have shown that GFRP reinforced concrete structures can maintain stability in a fire if measures have been implemented. Past experimental studies aimed to represent the behavior of common GFRP reinforced concrete members such as with bar splices in the fire-exposed regions. The results had shown that the loss of GFRP bond to concrete can cause a premature failure of such members. Later experimental studies avoided the spliced GFRP bars and focused on providing protected cool zones to guarantee adequate bond strength. This paper will study the challenges in establishing fire resistance for GFRP reinforced concrete beams and slabs. To have confidence in the fire resistance of a member, proof of a standard fire test such as ASTM E119 in necessary. The standard fire test of reinforced concrete beams or slabs requires the application of very large loads on a reinforced concrete member; this was initially developed based on the moment resistance of steel-reinforced flexural members. The steel reinforced members are designed for their full strength; however, GFRP reinforced concrete members are designed for service loads that are normally much smaller than their flexural resistance due to the large deflections. Section 8.8.3.1 of ASTM E119 requires the application of a superimposed load to simulate a maximum load condition. This load can be reduced when a national design code specifies limited design criteria. This paper will provide an understanding of realistic definitions of superimposed sustained loads throughout a fire test on GFRP reinforced members. It is imperative to distinguish these loading conditions in fire tests between steel reinforced concrete and GFRP reinforced concrete members. The suggested methods in ACI CODE-440.11-22 to achieve the desired fire resistance in a GFRP reinforced concrete members have been a great step towards the rational design considering the holistic behavior of such members in fires. Despite the advantages of these fire provisions, there might be new challenges that the industry (i.e., designers, constructors, and manufacturers) would face implementing the fire provisions. This study will provide some examples of how to effectively apply the fire provisions in the design of GFRP reinforced beams and slabs. The practical implications of this paper will answer the concerns of designers and GFRP producers on implementing the suggested fire provisions in ACI CODE-440.11-22.

Active Strengthening with Post-Tensioned CFRP Tendons

Eri Vokshi and Marcel Rey

External post-tensioning of structures is a known and understood strengthening method. Over the past twenty years, the use of externally bonded FRP, including pre-cured CFRP plates, has been widely adopted as an alternative strengthening solution to mechanically bonded steel plates. FRP materials are light, easy to deliver on jobsites, and corrosion resistant. Their strength utilization, however, is limited to the bond strength between the substrate and the FRP. External post-tensioning of CFRP plates allows for an excellent use of the material properties by introducing a post-tensioning load to a structure via two concentrated anchors. This type of CFRP system has been used for strengthening of bridges, buildings, caissons, tanks. This presentation will describe successful installation of external post-tensioned FRP systems, anchoring methods, and design considerations.

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