International Institute for FRP in Construction

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CICE2020/2021

10TH INTERNATIONAL CONFERENCE on FRP COMPOSITES in CIVIL ENGINEERING

8 - 10 December, 2021

Istanbul - Turkey

ABSTRACTS

Edited by

Alper Ilki, Medine Ispir and **Pınar Inci**

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10th International Conference

on FRP Composites in Civil Engineering

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December 2021

ABSTRACTS

PREFACE

The tenth International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2020/2021) is organized in Istanbul, Turkey on 8-10 December 2021. This conference is the most recent one of the official flagship conference series of IIFC (International Institute for FRP in Construction). Unfortunately, the conference had to be organized online due to Covid-19 pandemic. The topics of the conference cover All FRP structures; Bond and interfacial stresses; Concrete-filled FRP tubular members; Concrete structures reinforced or pre-stressed with FRP; Confinement; Design issues/guidelines; Durability and long-term performance; Fire, impact and blast loading; FRP as internal reinforcement; Hybrid structures of FRP and other materials; Materials and products; Seismic retrofit of structures; Strengthening of concrete, steel, masonry and timber structures; and Testing. All the papers submitted to the conference were carefully reviewed by the members of International Scientific Committee and the conference proceedings, which cover the full papers of the presented studies is published by the reputable publisher Springer.

This book includes the abstracts of 216 papers from 34 countries and other relevant information about CICE 2020/2021 conference. The great contributions of our keynote speakers, invited theme lecturers and all speakers are highly appreciated. The quality of the contributions submitted to CICE 2020/2021 was very high, and as organizers we had the chance to invite more than 100 papers to special collections/issues of ASCE Journal of Composites for Construction, Construction and Building Materials Journal, and Turkish Journal of Civil Engineering based on the suggestions of the reviewers.

On this occasion, I want to extend my sincere thanks to Professor Scott Smith, the president of IIFC and all the distinguished members of the IIFC Executive Committee, the members of the International Scientific Committee, the members of the Local Organizing Committee, the conference secretaries Dr. Pinar Inci and Mr. Kubilay Sahin, the administration and staff of Dekon Congress and Tourism Company, Istanbul Technical University, TUBITAK, Istanbul Governorship, Istanbul Metropolitan Municipality, Istanbul Convention and Visitors Bureau and all the sponsors of the conference.

Prof. Dr. Alper ILKI
Chair of CICE 2020/2021
Istanbul Technical University, Turkey
December 2021

CICE 2020/2021 MESSAGE FROM THE PRESIDENT OF IIFC

On behalf of the International Institute for FRP in Construction (IIFC), it is an honour to endorse this Book of Abstracts arising from the 10th International Conference on FRP Composites in Civil Engineering (CICE 2020/2021) that was held online 8-10 December 2021 and hosted from Istanbul, Turkey.

The CICE conference series is a flagship activity of the IIFC. Since first being held in 2001 in Hong Kong, CICE has been a unifying force around the world for 20 years now for those concerned with research and application of FRP composites in the built environment. Congratulations to the conference series and for our host CICE 2020/2021 in this 20th anniversary milestone year.

In late 2019 and onwards, the world became massively disrupted on account of the COVID-19 global pandemic. As of the running of CICE 2020/2021 (postponed from July 2020), the disruption of COVID-19 is still evident. I am heartened to see that our FRP community has remained engaged though. Engaged with research- and application-based projects that also advance the state of the art. This Book of Abstracts is testament to the excellent work that our community undertakes. This book will also serve as an extremely useful resource for years to come for a variety of stakeholders such as students, researchers, designers, suppliers, installers and asset owners.

I would like to thank all colleagues who have contributed to this Book of Abstracts as well as to the wider conference. This includes the conference Chair, Professor Alper Ilki, members of the Organising Committee and International Scientific Committee, Keynote and Invited-theme lecturers, Mini Symposia organisers and contributors, sponsors, authors, presenters, reviewers, and conference helpers.

In conclusion, can I ask all IIFC members to please promote the activities of IIFC to your networks and encourage colleagues to join our most dynamic organisation.

Professor Scott T. SMITH
President IIFC
The University of Adelaide, Australia
December 2021

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KEYNOTE LECTURERS

PENG FENG

Professor Feng received his PhD degree from Tsinghua University and joined the Department of Civil Engineering of Tsinghua University in 2005. His research field is the high-performance structures with emerging materials and advanced construction techniques, including FRP structures, FRPstrengthening, advanced concrete structures and 3D printing for construction.

He has published more than 90 journal papers. He is the inventor of 15 patents. He is the editor in chief of three Chinese National Standards on FRP. His contributions have been recognized by a number of awards/ prizes, including two National Awards for Science and Technology Progress of China (a First Prize and a Second Prize), IIFC Fellow, Young Scholar of Chang Jiang Scholars Program by MOE of China, Excellent Young Scientists Fund by NSFC, Mao Yisheng Beijing Youth Science and Technology Award, Young Scientist Award by CSCM.

KENT A. HARRIES

Kent A. Harries is Professor of Structural Engineering and Mechanics at the University of Pittsburgh, USA. He received his PhD from McGill University, Canada, and is internationally recognized in the fields of repair and retrofit with FRP and the behavior of pultruded FRP materials. He has published more than 280 peer-reviewed articles and three chapters and is Editor of one book. He serves as Vice President of IIFC, Senior Editor of Journal of Construction and BuildingMaterials and Chair of ACI Committee 440F (Repair of Concrete with FRP) and on numerous US and international codes and standards development committees primarily focusing on FRP and bamboo materials.

ANDREA PROTA

Prof. Andrea Prota is Full Professor of Structural Engineering at the Faculty of Engineering of University of Naples Federico II. He is currently Chair of the Department of Structures for Engineering and Architecture. He has published more than 500 scientific papers on journals or proceedings of national and international conferences.

He participates to the following National and International Scientific Bodies: Committee 440 of the American Concrete Institute (ACI), RILEM Technical Committee "Masonry Strengthening with Composite Materials", Member of the Commission of Ministry for Infrastructures and Transportation that developed the Guidelines for Classification of Seismic Risk of Constructions, Member of "Commission 7 – Sustainability" of fib, Member of "Commission 9 – Dissemination of knowledge" of fib, Member of the CNR Commission for technical provisions for constructions, Member of the Commission of Ministry for Infrastructures and Transportation that developed the Guidelines for Qualification of FRP materials.

THANASIS TRIANTAFILLOU

Thanasis Triantafillou is Professor in the Department of Civil Engineering and Director of the Structural Materials Laboratory at the University of Patras,Greece. He received the Diploma in Civil Engineering from the University of Patras (1985), and the MSc (1987) and PhD (1989) degrees fromMIT. He worked as Post-Doctoral Research Associate (1989) and as Assistant Professor (1990–1993) in the Department of Civil and Environmental Engineering, MIT, and as Visiting Professor in the Swiss Federal Laboratories for Materials Testing and Research – EMPA (summers of 1990–1991). He has 5 books; 30 chapters; 85 papers in international scientific journals; 145 papers in conference proceedings (including 18 keynotes); 15 invited papers in workshops; and more than 100 research reports.

LIBO YAN

The IIFC Distinguished Young Researcher Award Recipient (2021) Dr. Libo Yan is Professor in the Institute of BuildingMaterials, Solid Construction and Fire Protection in the Division of Organic and Wood-based Materials (FGO-iBMB) at Technical University of Braunschweig (TUBraunschweig) in Germany. He received his PhD in Civil Engineering (2015) from The University of Auckland, New Zealand.

He has published more than 75 refereed international journal papers, 6 chapters and over 20 peer-reviewed conference papers. He is Head of Science and Senior Scientist in the Centre for Light and Environmentally-Friendly Structures (ZELUBA®) at Fraunhofer Institute for Wood Research Wilhelm-Klauditz-Institut WKI. Currently, he is leading a diverse joint research group at FGOiBMB TU Braunschweig and ZELUBA® Fraunhofer WKI focusing on fundamental and applied-oriented research on hybrid structural and material systems, organic and inorganic building materials and wood-based hybrid materials, natural and synthetic fiber- and textile-reinforced polymer and cementitious composites, concrete and FRP recycling, and long-term durability of FRP materials and structures.

JIAN-FEI CHEN

The IIFC Medal recipient (2021) Prof. Chen received BEng and MSc degrees from Zhejiang University, China, and PhD degree from theUniversity of Edinburgh, UK. New materials/structures, ocean engineering applications, structural engineering and mechanics problems, silos, granular solids and FRP reuse/recycling are among his research interests.

He served as the fourth President of IIFC between 2014 and 2018. He has more thab 300 publications. His work has been widely cited and adopted by many international standards and design guidelines. He is one of the founders of the theory of FRP-strengthened concrete structures. According to an Elsevier research conducted for use for Academic Ranking of World Universities, he was one of the 150 Most Cited Researchers worldwide in Civil Engineering in 2016.

INVITED THEME LECTURERS

RIADH AL-MAHAIDI

Dr Riadh Al-Mahaidi is a Professor of Structural Engineering and Director of the Smart Structures Laboratory at Swinburne University of Technology in Melbourne, Australia. He also holds the position Vice President (International Engagement) at Swinburne. He received PhD degree in structural engineering from Cornell University in the United States.

Professor Al-Mahaidi published over 220 journal and 250 conference papers and authored/edited 12 books and conference proceedings. Prof Al-Mahaidi and his research group won the 2016 Engineers Australia Excellence Award for Innovation, Research and Development (High Commendation) for the Multi-Axis Substructure Testing (MAST) System they built at Swinburne. He was recently awarded the 2017 WH Warren Medal by Board of the College of Civil Engineers of Engineers Australia and the 2018 ARRB Research Impact Award.

FABIO MATTA

Fabio Matta is an Associate Professor in the Department of Civil and Environmental Engineering at the University of South Carolina, Columbia. He received his PhD from the Missouri University of Science and Technology. His group does research on construction materials and their performance, ranging from affordable earth masonry to advanced cement- and polymer-matrix composites, with an emphasis on extreme stressors. The results have been disseminated through over 100 peer-reviewed publications. Dr. Matta is an active member of ACI (Committee 241 – Nanotechnology of Concrete, and Joint ACI-ASCE Committee 446 – Fracture Mechanics of Concrete), and serves as editor-in-chief of the ASCE Journal of Composites for Construction, and associate editor of the ASCE Journal of Bridge Engineering and ASCE Journal of Materials in Civil Engineering.

NICOLA NISTICO

Nicola Nisticò obtained his PhD at the University of Firenze in 1994.
Since 1997 he is assistant professor of structural engineering at the Department of Structural and Geotechnical Engineering (Sapienza University of Rome) where, as associate professor, he currently teaches classes on Structural Design and is a member of the PhD Board.

His scientific activity addresses topics regarding a) expert systems b) seismic assessment and retrofitting of existing structures b) structural monitoring c) composite FRP materials.

THEODOROS ROUSAKIS

Theodoros Rousakis is an Assistant Professor of Repair and Strengthening of Concrete Members with Composites, at RC and Seismic Resistant Structures Lab, CE Departm., Democritus University of Thrace (DUTh, Greece). He has published 120 journal and conference papers and book chapters (scopus H index 21 since 2002). He is member of fib TG5.1 and TG8.1 and of the Editorial or Advisory Board in 5 international journals and regular reviewer in more than 40 journals.

YU-FEI WU

Yu-Fei Wu is a Professor at RMIT Uni. He obtained PhD in 2002 from Uni. of Adelaide. He has more than ten years of industry working experience as a professional structural engineer in China, Singapore and Australia.

Professor Wu has published about 150 archival journal papers with an H index 30 (ISI Web of Science). Professor Wu has developed numerous new structural theories and technologies and received numerous research awards including the Moisseiff Award from ASCE.

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ABSTRACTS OF KEYNOTE LECTURES

1496 - Integrated Seismic and Energy Retrofitting System using Textile-Reinforced Mortars Combined with Thermal Insulation

Thanasis Triantafillou[1*], Kyriakos Karlos[1], Aristomenis Tsantilis[1], Panagiotis Kapsalis[1]

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Abstract: Taking into consideration the seismic vulnerability of older buildings and the increasing need for reducing their carbon footprint and energy consumption, the application of an innovative system is investigated; the system is based on the use of textile-reinforced mortar (TRM) and thermal insulation as a means of combined seismic and energy retrofitting of buildings with masonry walls. Medium-scale tests were carried out on masonry walls subjected to out-of-plane and in-plane cyclic loading. Two key parameters were investigated experimentally: placement of the TRM in a sandwich form (over and under the insulation) or outside the insulation, and one-sided or two-sided TRM jacketing. A simple analytical method is developed and found in good agreement with test results. Additionally, numerical modeling is carried out, and it is also found in good agreement with test results. From the results obtained in this study it is concluded that TRM jacketing may be combined effectively with thermal insulation, increasing the overall strength and energy efficiency of the masonry panels in unreinforced masonry or masonry infilled buildings.

Keywords: Combined retrofitting; masonry; seismic; textile reinforced mortar; thermal insulation.

1499 - Fast and Low Impact Retrofit Using Advanced Materials for a Diffused Seismic Risk Mitigation

Andrea Prota[1] *

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**Corresponding author, aprota@unina.it*

Abstract: Existing reinforced concrete (RC) and masonry structures (particularly buildings and bridges) may be affected by significant deterioration and often need to be upgraded mainly to stop and/or delay material deterioration or to meet the new mandatory seismic design requirements. Applications of advanced materials for retrofitting and upgrading existing structures have been rapidly grown in past years because of their several advantages with respect to traditional strengthening systems. In the case of buildings, seismic upgrading performed as prevention measure needs to meet the strict requirement of avoiding people to leave and so being compatible with the daily functions during works execution: therefore, this crucial aspect has to control the conceptual design of retrofit interventions. These remarks have introduced new challenges in the development of novel advanced materials-based strengthening solutions for the seismic upgrading of deficient existing buildings that can be applied wholly from the exterior of the building. The experimental validation of such solutions and the relevant calibration of reliable design formulations for future seismic risk mitigation strategies is the main focus of this work. This paper outlines the basic principles of advanced materials-based seismic upgrading strategies on existing RC and masonry structures in order to avoid the most common brittle and premature failure modes. An overview of different experimental investigations carried out over the last two decades at the Department of Structures for Engineering and Architecture of University of Naples Federico II is presented. The experimental programs confirmed the effectiveness of such fast and low impact methodologies for the definition of design-oriented procedures for retrofit solutions based on advanced composite materials.

Keywords: seismic retrofit, fast and low impact interventions, innovative materials, resilient structures, seismic risk reduction.

1500 - FRP Confined Concrete: What, Why, and How?

Peng Feng[1]*, Jia-Qi Yang[2], Zhiyuan Li[1]

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Abstract: The post-yield hardening (PYH) behaviour is an important character of FRP confined which has been studied by researchers worldwide for decades. At the phenomenon-based level, the authors propose a 3D geometrical method to interpret the mechanisms of analysis-oriented models. This method unifies most existing analysis- and design-oriented models. For the mechanism-based study, the physical behaviour of the FRP confined concrete is revealed by X-ray computed tomography (CT), and the initiation and propagation of the internal cracks were captured by the scanned images. Further, path dependency of FRP confined high-strength concrete (HSC) and nonlinear biaxial behaviour of FRP tube are modelled using the 3D geometrical method. Finally, this paper provides an introduction to the recent development of composite structural elements from the authors' research group, which can maximize the confining efficiency and can improve the structural performance significantly.

Keywords: Confined concrete, Analysis-oriented model, CT scanning, Biaxial behaviour, Composite structures.

ABSTRACTS OF INVITED THEME LECTURES

1254 - Analytical Identification of Stress-Strain Relationship of Concrete in FRP Confined Columns

Yu-Fei Wu[1, 2]

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Abstract: The stress-strain relationship of concrete is different under different stress-strain conditions, load paths and environments. Identification of the stress-strain relationship of concrete for different structures and design conditions is critical to the engineering design of structures. As direct measurement of local stress is impossible without interrupting the original local stress-strain condition, various indirect methods have been developed to derive stress-strain relationships of concrete. An analytical method for deriving the stress-strain relationship of concrete from eccentrically loaded column tests is reported in this lecture, which involves rigorous mathematical derivations and rational analytical studies. Detailed and rigorous equations and computational procedures for columns with an arbitrary shape of cross-section are obtained. Instability of calculated stress-strain curve or large scattering of results, a critical problem of the analytical method, is resolved through proper selection of equations and computational procedures. Application of the method reveals the 'real' shape of the stress-strain relationship of confined concrete under eccentric loading.

Keywords: Concrete, FRP confinement, stress-strain relationship, column test, eccentric loading.

1368 - Design of an FRP Cable-stayed Pedestrian Bridge. Morphology, Technology and Required Performances

Attilio Quadrino[1], Marco Damiani[1], Rosa Penna[2], Luciano Feo[2], Nicola Nisticò[1*]

[1] *Sapienza University of Rome, Department of Structural and Geotechnical Engineering*
[2] *University of Salerno, Department of Civil Engineering*
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Abstract: In the past, a pilot project started at the Salerno University to conceive a pedestrian FRP bridge in the campus placed in Fisciano. The project gave the opportunity to start a cooperation among the authors and the result is the preliminary design of a cable stayed bridge, that will be presented after a description of worldwide FRP bridge realizations, including two pioneering cable stayed bridges: the Aberfeldy and the Kolding. The proposed six-span bridge has a total length of 185 m: a) antennas and decks are assembled through PGFRP elements; b) the PCFRP cables are anchored through a mechanical system optimized by defining the barrel and wedge angles. The solution is presented and discussed with regard of pedestrian comfort, joints and cable system. Specifying that dynamic effects due to wind action are under study, it can be concluded that the Capacity/Demand safety factor resulted greater than one as far as damage and ultimate limit states are concerned.

Keywords: GFRP, Cable Stayed Bridges, Connections, Structural Design.

1409 - Strengthening and Repair with Advanced Materials and Hybrid Techniques for Increased Resilience of RC Structures with the use of Pseudo-Dynamic 3D Finite Element Analysis

Theodoros Rousakis

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Abstract: This paper presents a critical review of advanced retrofit materials and recent techniques that may be utilized in earthquake resistant redesign of reinforced concrete structures to increase their resilience and safety. It also discusses some open design recommendation-related issues that may jeopardize structural member resilience. It reveals the potential of the Elastic Redistributable Uniform Confinement (ERUC) mechanism and concept and the contribution of relevant techniques in addressing some of the open issues. There is an urgent need for large scale dynamic experiments according to the fundamental 'design assisted by testing' procedure. Besides, the development of the framework for advanced dynamic 3-dimenional Finite Element (FE) modelling could support analytically these significant tasks. This study presents pilot pseudo-dynamic analytical studies on the Elastic Redistributable Uniform Confinement technique through external continuous spiral composite rope strengthening of concrete as well as on the FRP jacketing of RC columns. Three-dimensional FE modeling may help minimize required experimental validation of emerging techniques for seismic protection of brick infilled RC frames through highly deformable polymer joints or through externally bonded fiber grids with highly deformable polymers. Finally, it may help identify additional design parameters, enable further optimization of different hybrid retrofit techniques and enhance resilience and safety of concrete members.

Keywords: resilience, reinforced concrete, FRP, dynamic, finite element

1498 - An Experimental Study on Concavely Curved Soffit Reinforced Concrete Beams Externally Bonded with FRP

Riadh Al-Mahaidi[1*] ,Khattab Al-Ghrery[1,2],Robin Kalfat[1],Nazar Oukaili[2]

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Abstract
Externally-bonded (EB) fibre reinforced polymer (FRP) retrofitting system has emerged as a promising strengthening technique to improve flexural performance of concrete structures. This paper presents the results of an experimental program studying the behaviour of concavely-curved soffit reinforced concrete (RC) strengthened in flexure with EB carbon fibre reinforced polymer (CFRP) composites. Thirty-two RC beams were statically tested in this program. Of these beams, twenty-three were curved soffit beams with varying degree of curvature ranging between 5mm/m and 20mm/m, and nine beams were constructed with flat soffit as control beams. The ultimate capacity, failure mode, flexural stiffness, and the ductility of these beams are analysed and discussed. Based on the experimental results, concavely-curved soffit RC beams with the smallest degree of curvature strengthened with EB-CFRP performed better than beams with higher degree of curvature strengthened with similar CFRP system. This study identifies gaps of knowledge in existing design guidelines and codes and presents recommendations for designers on EB-CFRP technology.

Keywords: flexure strengthening, externally bonded, EB-FRP, carbon fibre reinforced polymer, CFRP, reinforced concrete, curved soffit beams, premature de-bonding.

ALL FRP STRUCTURES

1136 - Structural Re-Use of FRP Composite Wind Turbine Blades as Power-Line Utility Poles and Towers

Ammar Alshannaq[1], Lawrence C. Bank[1], David Scott[2], Jamieson Pye[1], Mehmet Bermek[1] and Russell Gentry[1]*

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Abstract: The production of wind energy worldwide has increased 20-fold since 2001. Composite material wind turbine blades are beginning to come out of service in large numbers. In general, these de-commissioned structures, composed primarily of glass fibers in a thermoset matrix and generally between 13 and 80 meters long, are demolished and either landfilled or incinerated. This research seeks to establish structural re-use applications for wind turbine blades in civil engineering infrastructure. This paper presents design concepts along with materials and engineering analysis for high voltage electricity transmission structures made from re-used wind turbine blades. This re-use application targets wind blades in the 25 to 50-meter overall length range, with single blades considered for use as cantilevered poles, and multiple blades used as replacements for waist-type truss or guyed towers. Strengths of the composite materials are established from coupons cut from de-commissioned wind blades – and section properties are established from blade geometries acquired using LiDAR scanning, through proprietary algorithms developed as part of the research effort. The section analysis is based on two common commercially available blades in the European and U.S. markets: the Vestas V52 and the Clipper C96. The paper reports on preliminary strength design allowables for the typical wind blade laminates and uses these as the basis for design under gravity, wind, and ice loading. Preliminary design of connections and physical mockup testing of these connections are presented

Keywords: Wind Turbine Blades, Recycling of Composites, Adaptive Re-Use, Compression Testing.

1350 - Maintenance and Structural Check of an All FRP Pultruded Construction

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Abstract: The proposed research focused on the maintenance and structural check of the first all FRP (Fiber reinforced polymer) pultruded construction built in Italy in the 2018. The proposed steps have been mainly in the frame of the joint's efficiency evaluation from the local point of view, and in that of visual inspection from a general point of view. By the way, the joint made by bolts are the more potential weak part in these type of constructions. The construction – all FRP made unless steel bolt – has been the consequence of a specific call and is built in the Iuav University Campus in Venice. The structural check is developed through cyclic in situ analysis of the joint bolted efficiency, specifically by means moment toque value applied evaluation and visual damage detection also considering closed formulas already available both for all FRP bolted joints and similar ones as well as connections made by steel and wood. Bolt monitoring is managed by means of a controlled tightening torque wrench which is used to detect the tightening torque for each bolt in the structure. To calculate the friction coefficient used, it was chosen to use the experimental formula on the determination of the μ. For the research, it was decided to use two different friction coefficients to calculate the tightening of the knots. The final aim of the research is to show the results of the structural controls and discussed in the framework of the general performances foreseen for all FRP structures.

Keywords: Maintenance, All FRP structures, Bolted connections, Pultruded elements, Hollow profiles.

1459 - Concept And Preliminary Test of the Intelligent FRP Bridge Deck for the Vehicular Bridges

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Abstract
The paper describes the concept of the smart FRP composite bridge panel with integrated distributed fibre optic sensors (DFOS), intended to monitor its behavior under live load. The system consists of continuous sensors, thanks to which it is possible to measure every part of the panel and the obtained response of the structure is comprehensive. The sensors are placed inside the laminates, thanks to which they are inseparably and securely connected with the structure. This solution required production tests to develop a durable and mass-produced solution. The final effect is an intelligent panel that can diagnose its condition based on algorithms and indicate the occurrence of anomalies.
The idea of placing fiber optic sensors in the material required first and foremost material tests, which, apart from obtaining data on the material itself, allowed to verify the readings from the DFOS system in relation to typical, discrete measurement systems. Subsequently, production tests were carried out on full-height sandwich panels by placing sensors in both the outer and inner laminate. After the preliminary tests were carried out, detailed calculations of the panels under the design load as components of the bridges were made. In the last stage, various types of connections were designed, allowing the FRP panel to be joined with conventional girders: steel and concrete, as well as connections between individual segments of FRP panels.

Keywords: deck, bridge, sandwich, optic sensor, DFOS.

1476 - Finite Element Modeling and Statistical Analysis of Fire-damaged Reinforced concrete Columns Repaired Using Smart materials and FRP Confinement.

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Abstract. Practical testing for observing the failure modes is expensive, time consuming and often limits the pace of research progress. Moreover, because of the limitations of equipment, the existing structures cannot be tested at ultimate failure and scale effect is not observed on large scale experimentally. Thus, numerical modeling and statistical analysis is required for prediction of the behavior of fire damaged and fire-damaged repaired structures. This Paper explores the regression models and Finite element studies to predict the load-deformation response of bolstered concrete columns, damaged through exposure to heat at 300^0C, 500^0C and 900^0C, strengthened using smart materials and confined by carbon fiber reinforced polymers. using Finite Element Modeling Software Non-linear analysis capable of predicting the axial load-deformation performance of undamaged, fire damaged and fire-damaged circular reinforced concrete columns, was prepared by various confinement techniques and SPSS Software was used for Regression modeling (Linear, multiple, and Quadratic). The obtained results showed that regression equations and numerical modeling offered a better alternative to the experimental methods. High correlation coefficient r and coefficient of determination r^2, more than 90%, for all developed equations, confirmed it as an excellent fit statistical model for prediction of axial load capacity and axial deformation. Similarly, the response predicted by numerical modeling showed minor difference i-e less than 10 % with that of experimental. Thus, it can be concluded that, the numerical modeling and prediction formulae agree quite with the experimental results and can be used as alternatives for prediction of loads and deformations.

Keywords: Fire-Damaged Columns, Smart construction materials, Numerical modeling, regression modeling, Abaqus, SPSS

1485 - Flexural Performance of BFRP Bar Reinforced High-Strength Concrete Beam

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Abstract: Although fiber reinforced polymer (FRP) can improve the bearing capacity of concrete structures, it always shows the brittle failure. This paper used high strength concrete RPC combined with BFRP bar to produce a new type of beam. The results of a four-point bending test shown that: the RPC-BFRP beam presented a plastic failure model as its load-deflection curve was similar to the steel bar RC beam. Otherwise, the BFRP bar reinforced normal concrete beam gave out a brittle failure as its load-deflection curve showed a bilinear model.Due to the higher utilization efficiency of BFRP bars as well as the high strength of RPC, the cracking load and the ultimate load of RPC beams were significantly higher than that of normal concrete beams. The new type RPC-BFRP beam showed a positive effect on both the flexibility and bearing capacity.

Keywords: BFRP Bar,Reactive Powder Concrete(RPC),RC Beam,Plastic Failure Model, Flexural Properties.

BOND AND INTERFACIAL STRESSES

1006 - Experimental Study on Comparison of Cyclic Bond Behavior of Ribbed and Sand-Coated CFRP Bars in High Strength Concrete

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Abstract
Although monotonic bond tests are available in the literature, limited experimental studies exist for cyclic loading conditions. To fill this gap, this work describes results from cyclic pull-out tests of eleven specimens with Carbon Fiber Reinforced Polymer (CFRP) rebars embedded in high strength concrete (f_{ck}> 50 MPa). Six of the samples were sand-coated while the remaining five were ribbed carbon fiber rebars to account for various bond conditions. CFRP rebars were concentrically embedded into U-shaped 350mmx350mmx300mm concrete blocks that provided sufficient development lengths. Rebar surfaces and development lengths with multiples of rebar diameters of $5d_b$, $10d_b$, $15d_b$, $20d_b$, $25d_b$, $30d_b$ and $40d_b$ were taken as the main parameters in this experimental work. Both tension load versus slip relationships and CFRP bar strain measurements were obtained and presented. In order to observe the distribution of the tensile stresses between the concrete and embedded part of the CFRP bar, three strain gauges were attached on the surface of each bar before pouring the concrete. During the tests, typical bond slip (i.e. debonding) and concrete splitting failures were observed. According to the experimental data obtained in this work, bond strengths were in the range of 7~11 MPa and 9~14 MPa, for the sand-coated and ribbed CFRP bars, respectively. These values indicate that the bond strength obtained for ribbed rebars is considerably higher, and therefore, it is necessary to take into account the change in the bond strength of CFRP rebars embedded in RC elements according to the rebar surface conditions. When the obtained results are compared with current specifications, it is seen that relationships and limitations proposed for the design are not in good agreement with the experimental data obtained in this work. The evaluation of specifications has shown that the Canadian CAN.CSA.S806 and Japanese JSCE-E131 codes remain on the safe side while the American ACI 440 code does not produce reliable results for the class of surface conditions considered here since the obtained design capacities using the ACI formula are very close to the experimental capacities without any safety factor. Bond stiffness's of specimens has decreased as number of load cycles has increased. Cyclic loading reduced the bond capacity of the specimens by maximum 40%.

Keywords: Bond Strength, CFRP, Cyclic Loading, High Strength Concrete, Pull-out Tests.

1009 - Bond Behavior of Basalt Fiber-reinforced Polymer Bars Embedded in Concrete Under Monotensile and Cyclic Loads

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Abstract: This study evaluates the static and fatigue bond behavior in basalt fiber-reinforced polymer (BFRP) bars embedded in concrete. For bond behavior under a mono-tensile load, BFRP bars with four types of surface patterns (round, rectangular, cross-winding, and spiral-winding) were adopted, and 20 groups of rib parameters were introduced for round-type BFRP bars. The bond–slip relationships and the influences of the above parameters on bond behavior were investigated. An analytical model for simulating the relationships of full bond slip was studied by data fitting. For bond behavior under cyclic loads, the relationship between stress levels and the number of cycles was investigated, and the slip of round-ribbed BFRP bars was studied with respect to the number of cycles. The results showed that the rectangular, cross-winding, and spiral-winding ribbed bars experienced serious wear, and that the average bond strength was approximately 80.6% of that of the round-ribbed bars. Thus, the bond behavior of the round rib is superior to those of the other surfaces. In addition, a bond–slip constitutive model for a BFRP bar is proposed, representing four main stages: a micro-slip stage, a slip stage, a descending stage, and a residual stage. Under cyclic loads, an equation was proposed for predicting fatigue life with a regression coefficient of 0.880, and a development law of slip was characterized as three stages: the linear increase stage, the steady increase stage, and the sharp increase stage, respectively.

Keywords: basalt fiber-reinforced polymer (BFRP), rib parameters, bond behavior, bond–slip constitutive law, fatigue life

1016 - Evaluating the Bond Characteristics of Intermediate and Ultra-High Modulus CFRP Laminates Adhered to Steel

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Abstract. Externally bonding Carbon Fiber Reinforced Polymer (CFRP) to steel, as a means of increasing the load carrying capacity of steel and concrete-steel composite beams, has become popular over the last couple of decades. When compared with traditional Intermediate Modulus (IM) CFRP, and due to the elastic modulus being higher than that of steel, high modulus (HM) and ultra-high modulus (UHM) CFRP laminates provide substantial load transfer in steel beams prior to yielding of steel. Several studies have been conducted on the bond between steel and CFRP, addressing the different failure mechanisms. Several bond-slip relations have been proposed, primarily for IM CFRP, based on cohesive failure within the bonding epoxy adhesive. This study aims to develop bond-slip models for both IM and UHM CFRP laminates bonded to steel, focusing on failure due to debonding at the steel-adhesive interface. Double lap shear tests were carried out using both IM and UHM CFRP laminates and the behavior of the specimens are compared with the finite element model results based on the developed bond-slip models. The double-lap shear joint stiffness was found to be higher for the UHM CFRP-steel bond, while the interfacial fracture energy was found to be higher for the IM CFRP-steel bond.

Keywords: Double-lap shear joint, finite element, CFRP strips, ultra-high modulus, bond-slip relation.

1039 - Thermo-mechanical bonding behaviour of CFRP NSM system using cement-based adhesive

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Abstract
Near surface mounted (NSM) strengthening technique, using fiber reinforced polymer (FRP) composite materials, is one of the most promising solutions for dealing with the deterioration problems of current reinforced concrete (RC) structures. However, intense research is still ongoing to keep improving this technique in the cases where its application shows limitations, e.g. in cases of fire hazard. The bonding in NSM systems is usually guaranteed by polymeric matrices like epoxy adhesives. However certain drawbacks result from the use of these adhesives, such as low resistance to elevated temperatures. This characteristic leads to premature failure under these circumstances, preventing the mobilization of the exceptional load carrying capacity of carbon fibers. Thus, the development of solutions involving alternative adhesives seems technically and economically relevant. Cement-based materials, which are incombustible and show low thermal diffusivity, show great potential as a valid alternative. Recent investigations suggest the possibility of transferring stresses between the NSM system and concrete substrate using cementitious matrices. However, the performance of these materials in different loading conditions, including high temperature exposure, need to be better explored.
This paper presents a study on the characterization of the bonding performance of CFRP NSM strengthening technique with cement-based adhesives using innovative surface treated carbon laminates installed into deep grooves. The CFRP laminates used in this study were manufactured specifically with sand-treated surfaces to improve the bonding performance between CFRP and cement-based adhesive by taking advantage of the better grip of the increased roughness surfaces. The results of the pull-out tests in ambient conditions, as well as after the exposure to elevated temperatures, are discussed.

Keywords: CFRP, High temperature, NSM, Cement-based adhesive, Surface treatment.

1108 - Experimental Study on Increase of Bonding Strength of FRPReinforcement in Concrete

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Abstract: In the last two decades, the use of fiber-reinforced polymer (FRP) bars is of great interest to reinforce concrete beam structures due to its high specific strength, effective corrosion resistance, and low cost fabrication. Therefore, the flexural performance of these reinforced concrete beams containing FRP bars has been investigated by researchers for years with great interest. According to these investigations, one of the major problems is weak bonding strength between these bars and concrete material. Since, this major problem causes low flexural capacity, high deflection, and high crack widths for the reinforced concrete beams. Hence, the use of FRP bars by engineers does not sufficiently become widespread and also the engineering applications of these useful materials are still limited today. In this study, it is aimed to present an applicable solution regarding the bonding failures of the FRP bars in structurally reinforced concrete beams. For this solution, reinforced concrete beam samples were produced by using FRP materials on which knotted structures were formed. Then these samples were tested under 3-point bending tests. Furthermore, smooth-surfaced FRP bars and traditional deformed steel rebars were also used as reinforcing materials in the concrete beam samples for the comparison of the flexural capacities of each sample in order to investigate the effects of the reinforcing materials on the bonding strength. To conclude, the knotted FRP bars provide a significant contribution on the flexural capacity due to the increase of the bonding strength between the reinforcing material and the concrete in the beams.

Keywords: FRP reinforcing bar, fiber-reinforced concrete, interfacial bond strength, adhesion.

1225 - Fatigue Behavior of FRCM Strengthened RC Beams: State of the Art and Future Developments

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Abstract: Numerous reinforced concrete (RC) structures are subjected to cyclic loading that may decrease their service life due to the occurrence of fatigue issues. Externally bonded (EB) fiber-reinforced composites have proven to be an effective solution to increase the fatigue life of RC members due to the stress re-distribution from the internal reinforcing steel to the external composite material. Besides, the effectiveness of fiber-reinforced composites is related to the quality of bond between the composite and the concrete substrate. Thus, the bond fatigue response should be investigated as well as the overall fatigue response of the strengthened RC element. Within the broad family of fiber-reinforced composites, those comprised of high-strength fiber textiles embedded within an inorganic matrix, which are generally referred to as fiber- (or fabric-) reinforced cementitious matrix composites (FRCM), showed promising results as a strengthening and retrofitting solution for RC structures. However, limited research has been carried out to investigate the fatigue behavior of the bond between the composite and the substrate and therefore the overall contribution to the fatigue life of the strengthened RC member. This paper presents a state-of-the-art on the fatigue behavior of RC beams strengthened in flexure with different FRCM composites. Furthermore, preliminary results of an ongoing experimental campaign aimed at studying the bond fatigue behavior of polyparaphenylene benzo-bisoxazole (PBO) FRCMs through a modified-beam test set-up are presented and discussed.

Keywords: fatigue; bond; modified beam test; fiber-reinforced cementitious matrix (FRCM).

1226 - Numerical Study of the Effective Lap-Splice Length of FRCM Composites

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Abstract. Fiber (or fabric) reinforced cementitious matrix (FRCM) composites represent an attractive alternative to fiber reinforced polymer (FRP) composites as externally bonded reinforcement (EBR) of existing reinforced concrete (RC) and masonry structural members. Although FRCM composites generally provide lower mechanical properties than FRP composites, they are permeable to vapor, can be removed with limited damage of the substrate, and have good resistance to relatively high temperatures. FRCM composites have been increasingly adopted to strengthen existing masonry members, such as walls, vaults, and domes. Due to the large surface of these members, different pieces of fiber textile (fabric) need to be overlapped (i.e. lap-spliced) to guarantee the stress-transfer between composite and substrate for the entire strengthened surface (excluding the anchorage length). Therefore, the lap-splice length represents a fundamental parameter for the effectiveness of the externally bonded reinforcement. However, limited work was carried out to investigate the stress-transfer mechanism between lap-spliced fiber layers.
In this study, a proposal to verify the minimum lap-splice length needed to guarantee the FRCM composite bond capacity in the case of overlapped textile, referred to as the effective lap-splice length, is put forward. The proposal is based on the comparison of the results of clevis-grip tensile tests and direct shear tests and it is validated by means of non-linear finite element numerical models of a PBO FRCM composite. The test procedure proposed can be used to verify the effective lap-splice length of FRCM composites required by current acceptance criteria and initial type testing procedures for inorganic-matrix composites.

Keywords: fiber-reinforced cementitious matrix (FRCM) composite, lap-splice, bond, finite element model, cohesive material law.

1341 - Influence of Elevated Temperatures on the Bond Between CFRP Strips and Concrete Using the NSM Technique - Definition of Local Bond vs. Slip Laws

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Abstract
This paper presents experimental and numerical investigations about the effects of elevated temperatures on the bond behaviour between concrete and carbon fibre reinforced polymer (CFRP) strips installed according to the near-surface mounted (NSM) technique. Firstly, single-lap shear tests were performed on concrete prisms strengthened with CFRP strips inserted into slits pre-cut in the concrete cover and bonded with an epoxy-based adhesive. The specimens were heated up to the target temperature (from 20 to 270 °C, measured in the adhesive) and then loaded up to failure while the temperature was maintained constant. The experimental results show that with increasing temperatures (i) the bond strength is significantly reduced, and (ii) the failure mode changes from CFRP tensile failure at 20 °C and 50 °C to adhesive failure in the CFRP-adhesive interface at higher temperatures. Secondly, a numerical procedure was developed to calibrate (based on the experimental results) the local bond *vs.* slip laws at different elevated temperatures. Overall, both the stiffness and maximum bond stress of the obtained laws decrease with increasing temperatures; in addition, the predicted load *vs.* slip curves fit well the experimental counterparts.

Keywords: CFRP strips, NSM strengthening technique, Concrete-CFRP bond, High temperatures, Experimental study, Bond *vs.* slip laws.

1396 - Generalized Method of Determining the Local Bond Slip Relationship of The Reinforcement Externally Bonded to Concrete

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Abstract: A new generalized method for evaluating the bond slip relationship of the interface between concrete and the externally bonded reinforcement is presented. The method is based on the relationship between the applied force and the displacement of the reinforcement at the loaded end. As no prior assumption on the detailed configuration of the bond slip relationship needs to be made using the generalized method, the obtained bond slip relationship can be regarded as a generalized relationship. The method was then used to evaluate the bond slip relationship of an investigated FRP-concrete interface reported in the existing literature, and the obtained relationship compared with several available bond slip models. It can be found that various bond slip relationships differ vastly even for the same FRP-interface, especially for the maximum bond stress and the corresponding slip as well as the the slip corresponding to the insignificant bond stress. In addition, the bond slip relationship obtained using the generalized method leads to the good prediction of the experimental results in terms of the global force versus displacement curve and strain distribution along the interface.

Keywords: Externally bonded reinforcement, FRP-concrete interface, bond slip relationship, generalized, global force versus displacement curve.

1411 - Bond Behavior of Steel Plates Externally Bonded on Concrete Elements

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Abstract: The traditional use of steel plates externally glued to Reinforced Concrete (RC) elements represents still a good solution for strengthening existing structures in comparison with the use of Fiber Reinforced Plastic (FRP) sheets and laminates due to relatively low prices, ductile stress-strain properties, possibility of increasing also the stiffness if serviceability performance needs to be improved, no limits for the strength increment percentage. However, few recent studies and guidelines are available for such a strengthening technique despite new and more efficient adhesive materials are currently available on the market aimed to make the bond behavior more and more efficient. Efficiency of strengthening technique is, indeed, mainly depending on bond behavior at the plate-concrete interface, which plays an important role in the possible debonding failure of externally strengthened elements and can be reliably investigated in detail by means of Finite Element (FE) models. In this paper, an in deep literature review of bond behavior of steel plates glued to concrete elements is reported by discussing the main parameters involved. Finally, an analytical mono-dimensional approach is developed and applied to simulate some experimental bond tests available in literature.

Keywords: Externally bonded strengthening, bond test, bond behavior, steel plate, mono-dimensional model.

1425 - Bond Assessment of GFRP Bars Embedded in Fiber-Reinforced Eco-Concrete

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Abstract: Steel corrosion is a major problem in the civil engineering industry, thus finding an effective alternative has been of main interest. One of these alternatives is glass fiber-reinforced polymer (GFRP) bar, as it has multiple advantages including: corrosion-free, nonconductive, and high strength-to-weight ratio. On the other hand, conventional concrete (CC) is not environment-friendly concrete due to its high CO_2 emission. Therefore, other replacements of Portland cement have been on the lookout. Some of the alternatives include fly ash and silica fume that can be added either partially or fully to make the concrete. In addition, adding fibers to the concrete has been of main interest, as it offers several advantages including crack control, and tensile capacity increase. In this study, a bond investigation was carried out using a pullout experiment to assess the bond-slip behavior between GFRP bars and fiber-reinforced eco-concrete (High-volume fly ash (HVFA) concrete) following the RILEM recommendations. The bond test was used owing to its structural significance and the lack of bond studies between such two sustainable materials (GFRP bar and HVFA concrete). The parameters of the study involved: concrete type (CC and HVFA), fiber type (steel and synthetic), bar type (GFRP and steel), bar size (13 and 19 mm), and embedment length (6.4 mm, and 12.7 mm). To make the assessment, the bond results of the GFRP-reinforced specimens were compared to those resulted from steel-reinforced specimens. The test results showed that the bond strength of GFRP bar was less than that of steel bar. Also, the addition of fibers to the concrete decreased the bond strength.

Keywords: Bond-Slip, Glass Fiber-Reinforced Polymer (GFRP) Bars, High-Volume Fly Ash (HVFA) Concrete, Steel Fibers, and Synthetic Fibers.

1428 - Use of Distributed Optical Fibre to Monitor the Crack Propagation of an Adhesively Bonded Joint During an ENF Test.

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Abstract: The floating production, storage and offloading units (FPSO) being generally in a tropical area, makes corrosion a fundamental ageing problem of these steel structures. Therefore, there is a strong need for proposing repair solutions having low impact on their exploitation. The owner of these units are highly interested in the development of "cold repair" in contrast with "hot works" which require to stop the production for security risks, like adhesively bonded FRP (Fibre Reinforced Polymer) patch which requires additional development, in particular in the design step. The design of these reinforcements needs a complete understanding of the mechanical state of the patch which is based on the different materials and interfaces properties. Fracture mechanics seems an interesting option to express the mechanical state of the patch and more particularly the risk to undergo interlaminar fracture or steel interface debonding failure before materials failure. The experimental definition of the required design values for such an approach (critical toughnesses) are generally obtained with common tests such as DCB (Double cantilever beam) or ENF (End notch flexure) tests.
The presented study is focused on the determination of the critical toughness in mode II through ENF (End Notched Flexure) test which can be done following some standards, such as ASTM D7905. A distributed optical fibre was used to verify the correct determination of the initial crack length, to determine the crack propagation during the test, and to monitor the fracture process zone length. The currently used methods, such as visual observation or Digital Image Correlation (DIC) of the crack front at the border of the sample, may indeed induce error if the crack is not straight. To compare these methods, the realized test was monitored using a distributed optical fibre placed in the centre of the lap width, in and on the specimen. Firstly, the issues related to the integration of this continuous optical fibre will be raised (insertion, precision resolution, measurement noise). Then, some experimental investigations will be described presenting different monitoring strategies using continuous optical fibre measurement and Digital Image Correlation technique (DIC). The obtained results will be analyzed focusing on the proper determination of the critical toughness of the adhesive. This will then be used to design and optimize the monitoring strategy of a wider experimental campaign.

Keywords:
Adhesive bonding, fracture mechanics, optical fibre, ENF, experimental investigations.

1444 - Loss of Bond Action in FRP-Strengthened Structural Elements: Modeling

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Abstract: The contribution focuses on the modeling of the interface between Fiber-Reinforced Polymer (FRP) and concrete. The customized procedure designed for this purpose is to be integrated into the finite element models: taking into account the possible loss of bond action will possibly lead to more accurate predictive results. Within the numerical algorithm the relative position of the initially coincident nodes on the interface is updated. Before any loading is applied, the degrees of freedom of the coincident nodes are coupled to model a perfect bond. In the loading history, the relative slip between initially coincident nodes occurs in conformity with a predefined slip – stress relationship. The numerical procedure is tested by modeling the progressive loss of bond action in a single-lap shear test specimen. The utilized empirical data are found in literature sources.

Keywords: FRP, concrete, interface, debonding, finite element modeling.

1460 - Bond Behaviour of GFRP Bars with Concrete at Normal and High Temperatures

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Abstract: Bond strength of glass fibre reinforced polymer (GFRP) rebars after long-term thermal conditioning was experimentally investigated in this study. In this paper, the results of pullout specimens with $5d_b$ embedment length are presented which is part of a much larger study on the effects of climate change on FRP-reinforced concrete structures. Specimens were constructed with 16 mm nominal diameter sand coated GFRP bars and conditioned at 50°C and 80°C for 4 months to investigate the effects of long-term thermal exposure. Relative humidity of 60% was maintained while conditioning the specimens. Long-term thermal exposure induced significant reductions in the average bond stress values of the specimens. Specimens conditioned at 50°C and 80°C observed 10% and 23% reductions in strength, respectively. Overall, the GFRP bars performed reasonably well and the retained average bond stress for specimens treated at 80°C was about 10.5 MPa which is still marginally greater than the minimum code specified limit of 8 MPa for design purposes. The 50°C thermal treatment was designed to study the climate challenges of continuously increasing temperatures and 80°C thermal exposure was devised to replicate the elevated service temperatures. Visual inspection revealed that GFRP bar's core had deteriorated after thermal exposure and the results of this study should be of interest to develop design guidelines to incorporate the thermal degradations.

Keywords: thermal degradation, bond strength, pullout specimens, beam bond strength, climate change.

CONCRETE STRUCTURES REINFORCED OR PRE-STRESSED WITH FRP

1023 - Testing a GFRP-Reinforced Concrete Bridge Deck Using a New Rolling Load Simulator

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Abstract: This paper investigates the behaviour of a full-scale slab-on-girder reinforced concrete (RC) bridge deck with two different types of internal reinforcement subjected to cyclic rolling loads. The overall dimensions of the deck were 15.24 m x 3.89 m x 0.21 m and the girder spacing was 3.05 m. One section of the deck had top and bottom grids of glass fibre reinforced polymer (GFRP) reinforcement and another had top and bottom grids of steel reinforcement, both designed according to the Canadian Highway Bridge Design Code (CHBDC). In this ongoing study, the bridge deck was subjected to cyclic loading using a novel Rolling Load Simulator (ROLLS) and the paper reports on the cycles completed to date, up to 3000 loading cycles. The stiffness degradation behaviour of the two different deck sections was monitored throughout the testing program using monotonic load tests at different cycling intervals. After 3000 stress loading cycles, the stiffness of the GFRP-reinforced and steel-reinforced sections was reduced by 35% and 28%, respectively. The GFRP-reinforced section experienced greater deflections and a larger decrease in flexural stiffness. The average maximum transverse reinforcement strain in the steel rebar under service load was 29% of yield strain while the GFRP bars were at 3.6% of their ultimate strain. The bridge deck will continue to be loaded up to 3M cycles to establish the fatigue performance of the two sections with different reinforcing materials.

Keywords: Bridge Deck, GFRP, Rolling Load Simulator, Stiffness Degradation.

1035 - Shear Response of BFRP-Reinforced Short Beams using Fiber Reinforced Concrete

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Abstract: Fiber reinforced polymers (FRP) composites are known for their high strength, lightweight and corrosion-resistance features. Adding basalt and synthetic microfibers in fiber reinforced concrete mixes (FRC) can improve the tensile strength, toughness and ductility as well as the post-cracking behavior of concrete element. This paper describes an experimental investigation to assess the shear behavior of fiber-reinforced short beams reinforced longitudinally with basalt fibers reinforced polymer (BFRP) bars. Three short beams without web reinforcement were constructed and tested under four-point loading test until failure. The ultimate shear capacity along with the load-deformation relationship and failure modes were studied. The experimental results showed a significant strength enhancement in beams reinforced with basalt and synthetic microfibers in comparing to plain concrete beam, as well as an improvement in overall beam ductility is noticed.

Keywords: Basalt microfibres, Synthetic microfibers, Short beams, BFRP bars, shear.

1045 - Structural Behavior of BFRCC Layered Deep Beams Reinforced with GFRP Headed-End Bars

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Abstract: In North America, structures in aggressive environments such as bridges and parking structures are prime examples for the use of fiber-reinforced composites (FRCs) due to their capability to control shrinkage cracking and improve impact resistance. Also, after cracking, more advantages of FRCs were reported such as increased energy-absorbing capacity and deformation capability, and improved load-bearing capacity. Reinforced concrete (RC) deep beams are one of the common components in such structures. Deep beams have higher load capacity compared to slender beams. They are characterized by their small span-to-depth ratio and they are usually designed using the Strut-and-Tie Model (STM). Recently, fiber-reinforced polymer (FRP) bars have been used as an alternative to steel bars to overcome the corrosion problems. However, due to its linear-elastic behavior and relatively low modulus of elasticity compared to steel, glass FRP (GFRP)-RC deep beams would be susceptible to deeper and wider cracks as well as lack of ability to redistribute stresses, which will adversely affect the capacity of such beams. On the other hand, contribution of the arch action mechanism to the shear strength in FRP-RC deep beams can be improved because of the relatively higher tensile strength of FRP bars in the tie.

In this study, a layer of basalt fiber-reinforced cementitious composite (BFRCC) was incorporated in the tie zone to examine its ability to enhance the overall behavior of GFRP-RC deep beams. Two large-scale RC deep beams reinforced with GFRP headed-end bars were constructed and tested up to failure. The specimens had a rectangular section of 250×590 mm and a length of 2,100 mm. The main variable was the incorporation of the BFRCC layer in the tie zone. The specimens were tested in a three-point bending setup over a clear span of 1.24 m with a shear span-to-depth ratio of 1.0. The test results confirmed the formation of the arch action mechanism in both beams. In addition, analysis of test results pinpoints that the incorporation of basalt fiber pellets in the tie zone of the beam improved its behavior and increased its load carrying capacity.

Keywords: deep beams, basalt fiber pellets, glass fiber-reinforced polymers (GFRP), headed-end bars, nano-silica.

1061 - Effect of Under-stressing on The Fatigue Strength of RC Beams Rehabilitated with NSM CFRP Reinforcement

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Abstract: Reinforced Concrete (RC) bridges are subjected to a growing traffic load along their service life. The rupture of steel rebars is the most dominant failure mode of RC beams under fatigue loads. Applying cyclic stresses below the fatigue limit improves the fatigue strength of metals, which also known as "under-stressing". This paper investigates the influence of under-stressing on the fatigue performance of RC beams rehabilitated with Near Surface Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP). The study includes four RC beams with dimensions of 152.4×152.4×1,521 mm. A strengthened and a non-strengthened specimens were tested under monotonic loading to obtain the flexural static capacity. A strengthened specimen was tested as a reference under constant amplitude cyclic stress without experiencing pre-fatiguing. In contrast, a non-rehabilitated RC beam was pre-fatigued to simulate the conditions of service loading. Later, the specimen was rehabilitated with NSM CFRP reinforcement and tested under the same cyclic load of the reference specimen. The rehabilitated RC beam had an improvement in the fatigue responses when compared to the reference strengthened specimen. Under-stressing had a major role in decelerating the fatigue crack propagation of steel rebars and in extending the fatigue life of the rehabilitated RC beam.

Keywords: Fatigue, Beam, Under-stressing, CFRP, NSM.

1077 - Thin Sandwich Elements Prestressed with CFRP Tendons

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Abstract: Sandwich panels exhibit an attractive choice for modern building envelopes. Innovative high performance materials such as non-corrosive carbon reinforcement make it possible to produce elements with thin layers, which fulfil the requirements of sustainable and durable building envelopes. The application of two thin facings made of high performance concrete (HPC) and a core of polymeric rigid foam (PU) can highly enhance the load-bearing capacity of sandwich panels providing a low weight at the same time. In order to enable large façade elements or wide-span roof elements, an additional prestressing with CFRP (carbon fibre reinforced polymer) tendons is advantageous. These prestressed slender sandwich elements have a high potential for economic savings in terms of material and transport as well as reduced time efforts during mounting.
The paper reports on experimental investigations during the development of planar elements made of carbon reinforced HPC and pretensioned CFRP tendons. The determination of the transfer length of CFRP tendons in HPC is described and the results of bond tests on small-scale sandwich elements under tensile and shear loads are shown. Furthermore, the influence of textile connecting devices on the load-bearing capacity was determined. With the conducted experimental investigations, the high potential and performance of sandwich elements prestressed with CFRP and a PU core can be shown.

Keywords: textile reinforced concrete, CFRP tendons, prestressed concrete, sandwich constructions, textile connecting devices.

1123 - Experimental Monitoring of Long-term Structural Behaviour and Prestress Losses of BFRP Pretensioned Beams under Sustained Loading

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Abstract: The recent interest in expanding the scope of application of Fibre Reinforced Polymers (FRP) in the construction industry has been a driver of copious research. The favourable mechanical properties of FRP make them suitable for internal reinforcement of concrete elements with specific service conditions. Nonetheless, the low Young modulus of glass fibre reinforced polymers (GFRP) and basalt fibre reinforced polymers (BFRP) has been a concern, as it negatively affects the serviceability performance of flexural composite reinforced concrete elements. Prestressing has emerged as a possible method for limiting the deflections and cracking and has been shown as effective in numerous papers. However, long-term behaviour of such structural members has not yet been investigated extensively; therefore, this paper aims to give information on long-term behaviour and losses of prestress of pretensions BFRP beams.
The experiment was conducted on six BFRP pretensioned concrete beams. The samples were of equal dimensions and reinforcement, with pairs of different prestress levels: two beams prestressed to 20%, two to 30% and two prestressed to 40% of the ultimate tensile capacity of the BFRP bars. The beams were then subjected to long-term sustained loading, equal to approximate working permanent loads. Strain level in the BFRP bars was electronically recorded, as well as deflections, surface strain and cracking of the elements. The paper presents the results of six months of continuous monitoring, as well as results of final destructive four-point bending testing.

Keywords: prestress losses, BFRP, long-term, PT beams.

1155 - Parametric Study of Slender Columns Retrofitted with NSM CFRP Rods

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Abstract: Corrosion of steel bars in reinforced concrete (RC) due to environmental exposure results in service life and durability reduction and subsequent premature failure of structures. Columns are considered as critical components of a structure. Partial or full loss of columns' steel reinforcement due to corrosion can potentially lead to the collapse of the entire structure. An effective retrofit procedure is required to restore the performance of these damaged columns. The present numerical study investigates the use of near-surface mounted (NSM) CFRP rods as a retrofit technique for eccentrically loaded slender columns that partially or fully have lost their internal steel reinforcement due to corrosive environment. The proposed numerical model is corroborated with experimental results available in the literature. A parametric study was conducted to study the effectiveness of the NSM CFRP rods retrofitting to structurally compensate for the lost corroded steel reinforcement of as-built columns for ten different scenarios. The performance of retrofitted columns was assessed through axial load versus moment response plots. The results indicate that the NSM CFRP rods were able to regain the reduction in strength caused by the loss of internal steel reinforcement of damaged columns. Whereas in some scenarios, axial load and moment carrying capacities were increased.

Keywords: FEA Modelling, FRP Strengthening, Eccentric loading, Near-surface mounting, Slender column.

1184 - Numerical Investigation on the Shear Behavior of Reinforced Concrete Beams Strengthened with Textile Reinforced Mortar Jackets

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Abstract: Textile reinforced mortar (TRM) is a composite material composed of fibers as textiles attached to inorganic binders like cement-based mortars. TRM has been found to be a promising alternative solution to fiber reinforced polymer (FRP) in retrofitting structures. In this paper, reinforced concrete (RC) beams were strengthened in shear by TRM to investigate their behavior. ANSYS software program was used to generate the finite element analysis (FEA) models of TRM strengthened RC beams. The beam model results were compared to that of an experiment in the literature for validation and they were in good agreement. The parameters considered in the study were the effective depth of the beam, and various loading conditions. The results revealed that the beam depth had a significant impact on the ultimate load of shear deficient reinforced concrete beams strengthened with TRM. The load capacity improved, and the TRM shear contribution decreased with the increase in the beam's depth. Besides, distributing the load resulted in increasing the TRM shear contribution.

Keywords: Finite element analysis, Mortar, Concrete beams, Shear strengthening, Textile reinforced mortar.

1190 - Axial Load Performance of GFRP-Reinforced Hollow Concrete Columns

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Abstract: The limited understanding on the nature of the internal stress formation in hollow concrete columns (HCCs) reinforced with steel bars often led to brittle failure behavior either by buckling of the longitudinal bars or concrete wall crushing. Moreover, the corrosion of steel bars in HCCs is a crucial issue due to their exposed inner and outer surfaces. This study systematically investigated the effect of major design parameters controlling the structural behaviour of HCC reinforced with Glass Fibre Reinforced Polymer (GFRP) bars under concentric compression loading. It focuses on investigating the effect of inner-to-outer diameter ratio (i/o), reinforcement ratio (ϱ), volumetric ratio (ϱ_v), and concrete compressive strength (f'_c). It also aims at demonstrating the effective use of GFRP bars as internal reinforcements for the reliable, safe and durable HCCs. Finally, this study critically discusses the stress mechanism difference between the hollow and solid concrete columns and identifies new simplified definition for the ultimate compressive strength capacity of the HCCs.

Keywords: GFRP bars, Compression, Hollow Column, Ductility, Confinement, Strength.

1258 - Unloading behaviour and analysis of GFRP prestressed concrete beams

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Abstract: Glass fibre-reinforced polymer (GFRP) bars present multiple advantages over conventional steel reinforcement including high strength-to-weight ratios and corrosion resistance. Whereas many studies are reported in the literature on the behaviour of GFRP-reinforced concrete members, the performance of GFRP-prestressed concrete beams has been the focus of only a few research works. Zawam et al., (2017) demonstrated the potential of GFRP for prestressing applications with satisfactory creep performance under sustained loading. Very limited information available regarding the unloading behaviour of concrete beams after being subjected to sustained loading. Such information would be beneficial for example in cases of concrete bridges during rehabilitation projects. Similarly, very few studies are available that describe the behaviour of GFRP-prestressed concrete beams. This study addresses both of these gaps through an investigation of the unloading behaviour of GFRP-prestressed/reinforced concrete beams after being subjected to different levels of sustained loading for a period of 300 days.

Keywords: Glass fibre reinforced polymer, prestressing, unloading, sustained load.

1297 - Numerical Investigation of a New Floor System with GFRP Stay-in-Place Forms and

Embedded I-Beams

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Abstract: A new hybrid floor system comprising embedded glass fiber reinforced polymer (GFRP) I-beams and GFRP stay-in-place (SIP) structural forms as bottom reinforcement and top GFRP rebar is developed for rapid floor construction. The SIP forms are flat plates with T-up longitudinal ribs spanning the 1200 mm spacing between the I-beams and supported on the bottom flanges of the I-beams. In this study, a robust three-dimensional finite element (FE) model is developed and is capable of simulating the concrete nonlinear behavior in tension and compression, composite failure of the FRP systems, and various contact types; including between SIP form and concrete; SIP form and I-beams; and the I-beams and concrete. Two independent flexural test programs, including tests by the authors and tests reported in literature, were used to calibrate the model. Following calibration, the FE model will be used in an extensive parametric study to investigate different parameters impacting the new floor system.

Keywords: FRP, Stay-In-Place (SIP) forms, Finite Element (FE), GFRP bars, Reinforced concrete, RC slabs.

1334 - Shear Code Provisions Applied to the Prediction of FRP Strengthened Prestressed I-Girders

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Abstract: Shear strength contribution of concrete, steel and FRP in case of strengthened prestressed I-girders is not well defined in the literature. Analytical design and prediction models give a lot of variation compared to the experimental observations. The suitability and effectiveness of analytical models in case of strengthened prestressed I-girders is an open research question. This paper compares the shear strength prediction based on the analytical models given in different codes or guidelines, when applied to FRP strengthened prestressed I-girders. This is benchmarked against a small experimental dataset taken from literature. It is concluded that the available design guidelines are not able to predict the shear strength of FRP strengthened prestressed I-girders. FRP shear contribution models derived for rectangular cross sections fail to capture the phenomenon of early debonding around the internal angles of the I-section and cannot be used for complex sectional geometries. The results reported in this paper are part of a wider study to investigate anchored FRP shear strengthening configurations, to avoid local de-bonding at the concave zones of complex cross-sections such as I-girders.

Keywords: FRP, I-girders, prestressed concrete, shear strengthening, predictive models.

1357 - FRP reinforcement to retrofit bridge pier after repair: experimental test results

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Abstract: Reinforced concrete (RC) bridge piers damaged after a strong earthquake are repaired. The damaged concrete and the steel reinforcement parts are replaced by rebar segments connected to the existing rebar parts by welding connections and by a self-compacting concrete jacket respectively. A modest transverse steel reinforcement, not sufficient to improve the seismic pier capacity, is used to simplifies the concrete cast in modest volumes. After the repair, a carbon fiber reinforced polymer (Carbon FRP) reinforcement is applied to enhance the pier ductility and the shear strength. Three RC circular columns, representative of piers, were repaired and reinforced by the proposed strategy to be tested in lab applying a deformation history due to a strong earthquake. The piers were able to sustain very strong seismic demand and therefore the proposed repair and retrofitting interventions are effective. The strain distribution of the Carbon FRP reinforcement was measured and discussed to increase the very modest database presented in the literature.

Keywords: Carbon FRP, experimental strain, bridge, repair.

CONCRETE-FILLED FRP TUBULAR MEMBERS

1073 - Combined Torsion, Flexure, and Axial Compression Applied to Concrete Filled FRP Tubes

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Abstract: This paper presents the testing results of four concrete-filled fiber-reinforced polymer tubes (CFFT) to evaluate their response under combined axial compression, flexural, and torsional loading. The first three samples evaluated each of the loading states individually, while the final sample tested a combination of all three loads. The presence of the axial compressive force was found to increase cracking strength by 178% in flexure and 105% in torsion while improving load retention after cracking. More importantly, combined loading was found to improve the flexural capacity by 34%, while reducing the torsional strength by 30%. This loading state had little effect on the flexural and torsional stiffnesses along with the maximum flexural deflection but reduced the twist capacity by 68%. Failure in the combined loading state was governed by the rupture of the tube resulting from high longitudinal tension on the bottom surface like in the case of pure flexure.

Keywords: CFFT, Concrete, Torsion, Bending, Axial.

1075 - Segmental Hollow Concrete Filled FRP Tubes (CFFT) for Wind Turbine Towers

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Abstract: Concrete-filled fibre-reinforced polymer (FRP) tubes (CFFTs) have been shown to be effective as both compression and flexural members in bridges. The main objective of this research is to extend this design concept to wind turbine towers. This study aims to evaluate the flexural performance of segmental and non-segmental hollow post-tensioned CFFTs (PT-CFFTs) through an experimental investigation. Four large-scale specimens have been constructed and will be tested under three-point bending, including three segmental hollow PT-CFFT specimens and one non-segmental hollow PT-CFFT control specimen. The specimens have been designed to study the influence of the following parameters on the performance of tapered hollow CFFT wind turbine towers subjected to bending loads: segmental construction methods for scaled wind turbine towers, contribution of outer GFRP tubes, and overlapping length between consecutive CFFT segments. The GFRP tube combined with the post-tensioned concrete system is intended to improve the constructability and structural efficiency of small scale wind turbines for remote areas such as the Canadian North. The optimal overlap length between two GFRP tubes required to develop the full flexural capacity of the CFFT system will be determined experimentally, and the feasibility of combining GFRP tubes, prestressing systems, and segmental construction in tapered wind turbine towers will be evaluated. In this paper, the relevant literature is reviewed and the preliminary experimental progress is presented.

Keywords: FRP, Post-tensioning, Segmental construction, Concrete, CFFT, Wind turbine towers.
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1103 - Experimental Behaviour of ±55° GFRP Filament Wound Tubes Under Uniaxial Tension and Compression

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Abstract: As a part of this study, 25 filament wound ±55° glass fibre-reinforced polymer (GFRP) tubes were tested in uniaxial compression and six in uniaxial tension. For the compression tests, tubes with two inner diameters (ID) were tested: 76.2 mm and 203.2 mm, as well as three nominal pressure ratings: 350 kPa, 700 kPa and 1050 kPa. Each compression specimen was cut such that the length was twice the outer diameter (OD). The compression test set-up is presented in Figure 1a. For each tube type, five identical specimens were tested in compression. Only two tube types were tested in tension: 76.2 mm diameter tubes with pressure ratings of 350 kPa and 1050 kPa. A novel test method presented in Figure 1b was used to test the tubes in tension. For each tube type, three identical specimens were tested in tension. The main test parameter was the effect of the D/t ratio on specimen stiffness and strength in both compression and tension. The tests showed that the tubes exhibit a nonlinear stress-strain response when loaded in both tension and compression and that, when loaded in tension, there is a significant post-peak behaviour. The tests also showed that the tubes were stronger in compression than in tension.

Keywords: GFRP, Tubes, Filament Wound, Compression, Tension

1194 - Flexural Performance of Post-Tensioned Rectangular Concrete-Filled FRP Tubes (CFFT) Beams Using High and Normal Strength Concrete

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Abstract: This paper presents the test results of an experimental study aimed at investigating the flexural behavior of prestressed high and normal strength concrete filled fibre-reinforced polymer (FRP)- rectangular tubes (CFFT) beams. Two unbonded post-tensioned (PCFFT) beams were constructed with different concrete compressive strength ranged from 40 to 70 MPa. All beams had identical cross-sectional of 305×406 mm^2. The beams were tested under a four-point bending. The test results confirm the feasibility of using post-tensioned rectangular CFFT system for flexural members. The results indicate that the PCFFTs beams are capable of developing very high inelastic flexural deformations and ultimate capacity. High-strength and normal-strength concrete prestressed CFFT beams show almost similar inelastic load-deflection behaviors. While increasing the concrete compressive strength from 40 to 70 MPa enhanced the initial stiffness and load before cracking. After cracking, however, prestressed CFFT beam constructed with high-strength concrete exhibit only a 7% increase in the ultimate flexural moment capacity with no significant change in the ultimate deflection compare to normal-strength concrete beam. The proposed analytical model based on partially confined concrete model successfully predicts the flexural moment capacity of the tested beams with satisfactory accuracy on average of 1.08±0.03. However, further experimental tests are needed to better understand the flexural behavior of PCFFTs with a wide range of concrete compressive strength.

Keywords: Prestressed, Concrete-filled tube, Post-tensioning, High-strength concrete, Confinement.

1299 - Influence of Filler Properties on the Axial Behaviour of Pultruded FRP Tubes

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Abstract: The low axial stiffness and high slenderness ratios of pultruded fibre reinforced polymer (PFRP) tubes make their axial behaviour is governed by the buckling issues. Increase the axial stiffness and support the PFRP walls against buckling can be obtained through filling with concrete. The improvement in the axial behaviour of PFRP tube-concrete columns depends on the properties of filler material and PFRP tubes.
In this study square and circular PFRP tubes were selected to investigate effects of cross-sectional shape on the improvement degree of the load capacity. The influences of fibre orientation and wall thickness were studied by considering two types for each PFRP tube sections. Two types of both normal concrete and lightweight perlite concrete were considered to fill PFRP tubes and to cover a range of variation in the filler modulus from 5 to 30 GPa. The length of PFRP columns was set to provide length -to lateral dimension ratio of 5. The results show that the stiffness of filled columns is increased as the modulus of concrete filler increases as well as, the load carrying capacity unless the transverse resistance of PFRP tube to the lateral dilation of the infilled concrete is low. Moreover, the post peak behaviour depends on the properties of filler and PFRP tubes. It is changed to be gradual reduction instead of sharp dropping of hollow PFRP columns. The findings would contribute to enhance the usage of PFRP tubes in application of civil engineering as it provides an approach to overcome the shortages that were controlled the axial behaviour of PFRP tube columns.

Keywords: Pultruded FRP tubes, buckling, concrete fillers, post-peak behaviour, load capacity.

CONFINEMENT

1106 - Key Parameters in the Calculation of the Reinforcement of Rectangular Columns with FRP. Review of Design Guidelines and Comparison with Experimental Results.

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Abstract: It has been shown after several studies, that in view of the need to strengthen the deficient columns of reinforced concrete (RC), one of the most attractive and used techniques to increase strength and strain capacity, is the confinement of concrete whit FRP (fibre reinforced polymers).
It is well known that the confinement of square or rectangular columns is less efficient than the confinement of circular columns.
Most of the experimental studies focused on the behaviour of small-scale concrete circular specimens. However, in practice, the most typical findings are the square / rectangular columns of reinforced concrete (RC) on a large scale, so that there is still significant uncertainty in the models used to calculate the reinforcement with FRP and their applicability (especially in the case of columns with rectangular section).
One of the key parameters in the prediction of the models is the ultimate strain of the FRP. Some models consider a strain efficiency factor of approximately 0.6, the value of which has been determined from tests on small-scale cylindrical specimens.
This paper presents an analysis of the design formulations proposed in the main published international guidelines and compares them with the experimental results of larger square and rectangular section specimens (intermediate and full scale).

Keywords: Design recommendations, confinement, RC columns, large scale, models.

1114 - Compressive Behavior of Masonry Columns Confined with Multi-layer SRG Composite

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Abstract: Steel-reinforced grout (SRG) is a type of composite used for structural strengthening applications. SRG is comprised of high-strength steel cords embedded in an inorganic matrix. In this paper, the results of an experimental study carried out to understand the compressive behavior of masonry columns confined by multi-layer SRG jackets are presented. Twenty-four confined and seven unconfined solid fired-clay brick masonry columns with a square cross-section were tested to failure under a concentric compressive load. Test parameters included the column corner condition, number of fiber sheet layers, and number of column faces the fiber sheets were overlapped (in the wrap direction), referred to herein as the number of fiber overlapping faces. SRG confinement was found to improve the compressive strength, ultimate axial strain, and energy absorption of the masonry columns. Results showed that the confined compressive strength, ultimate strain, and absorbed energy increased with the number of fiber sheet layers, however the increase in confined strength was not proportional to the number of fiber sheet layers. Rounding the column corners slightly increased the confined compressive strength. Increasing the number of fiber overlapping faces also increased the confined compressive strength, ultimate strain, and absorbed energy.

Keywords: Columns, Confinement, Masonry, Steel-Reinforced Grout (SRG) Composite.

1180 - Behaviour of Recycled Aggregate RC Columns Wrapped with CFRP under Axial Compression

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Abstract: Over last few decades, number of studies have been carried out which studies the properties of concrete specimen made with recycled aggregates. In general, the focus of these investigations was to evaluate the behaviour of such concrete under uniaxial compression, tensile splitting and flexural by using different percentages of recycled aggregates. Based on these studies declining trend of compressive, tensile splitting and flexural strength was observed as the percentage of recycled aggregates increased. Therefore, if structural columns are to be designed with recycled aggregate concrete (RAC), the decline in compressive strength of RAC should be catered using some strengthening technique. The use of carbon fibre reinforced polymers (CFRP) wraps with columns subjected to uniaxial compressive loads have shown to contribute significantly towards increase in load carrying capacities of columns. This study investigates experimentally, the response of fully wrapped reinforced concrete columns made with RCA with CFRP under uniaxial compression. Twelve 600 mm high reinforced concrete rectangular columns (150 mm × 300 mm) were used in the study. Out of twelve, six specimens were fully wrapped with unidirectional CFRP wraps and six were without wraps. Furthermore, columns were cast using RAC with 0%, 70% and 100% of RCA. It was found from the experimental investigation that the specimens with CFRP wraps performed better than columns without CFRP wraps, both in terms of axial compressive load and the ductility. Furthermore, it was also observed that the declining trend in compressive strength associated with RAC was overcome by the use of CFRP wraps.

Keywords: Recycled aggregate concrete, confinement, CFRP, strengthening, retrofitting.

1304 - Axial Behaviour of Damaged Concrete Columns Repaired with Novel Prefabricate FRP Jacket

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Abstract: A new type of prefabricated fibre reinforced polymer (FRP) composite jacket with an innovative joining system consisting of two interlocking edges and a locking has been developed for effective repair of damaged reinforced concrete (RC) columns. In this paper, the results of the experimental investigation on the evaluation of the effectiveness of this novel prefabricated FRP jacket in repairing RC columns with different levels of corrosion damage are presented. Full scale RC columns with 25% and 50% simulated steel corrosion damage and repaired with the novel FRP repair system was tested under concentric compressive load. The corrosion in the steel reinforcement was simulated by discontinuing the longitudinal bars in the middle part of the column and replacing with non-structural PVC pipes. The stiffness and strength capacity of these repaired columns was compared with damaged and undamaged columns. The results showed that the provision of the FRP jacket fully restored the axial stiffness and up to 99% and 95% of the axial strength capacity of columns with 25% and 50% corrosion damage, respectively. Theoretical analysis was also developed to predict the axial load capacity of the repaired columns considering the partial confinement provided of prefabricated composite jackets.

Keywords: Novel repair system, composite jacket, pre-fabricated FRP jacket, damaged concrete columns and corrosion damage.

DESIGN ISSUES GUIDELINES

1014 - Implementation of GFRP-Reinforced Concrete Draft Code Provisions in Design Examples: What Works and What Doesn't

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Abstract: The American Concrete Institute (ACI) currently has an approved design guideline for FRP-reinforced concrete: ACI 440.1R-15 *Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars*. Work is now in progress to develop a consensus-based standard design code for GFRP-reinforced concrete dependent to ACI's 318-14 *Standard Building Code for Structural Concrete*. The GFRP code language will generally follow the principles recommended in the ACI 440.1R-15 guide, with a number of significant changes that have resulted from recent research and the need to develop provisions in areas that the ACI 440.1R-15 guide does not address. Prior to approval by ACI, the proposed changes must be vetted in practical design situations. Accordingly, design examples consistent with the ACI draft code language have been developed and their solutions examined to study the impact that proposed code language may have on the design of GFRP-reinforced concrete members. This paper discusses one of those design examples to: (1) promote understanding and provide evidence that draft code provisions can be practically implemented in typical design situations; and (2) identify situations in which draft code language may require modification.

Keywords: GFRP, Codes and Design Guidelines, Design Issues, Case Study.

1074 - Reliability Analysis of FRP-Concrete Joint with or without Epoxy Interlocking Enhancement

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Abstract: External bonding of fiber reinforced polymer (FRP) composite with epoxy interlocking (EB-FRP-EI) enhancement has been proved to be able to significantly improve the strength of FRP-to-concrete joint according to experimental studies. However, there is no reliability-based analysis to study the effects of epoxy interlocking on the reliability index of FRP-concrete joint. This study investigates the effects of the number of grooves and the depth of each individual groove on the performance of external bonding of FRP composite with epoxy interlocking enhancement by reliability analysis. The reliability analysis of the strength of FRP-concrete joint with epoxy interlocking was conducted by utilizing first order reliability method (FORM). The results show that increasing the depth of each individual groove and number of grooves could significantly increase the reliability index value. For given FRP and concrete, there should exist a most effective and economical epoxy interlocking enhancement design with proper combination of depth of individual groove and number of grooves.

Keywords: epoxy interlocking; FORM; FRP-to-concrete joint; groove; reliability analysis

1146 - A Progressive Failure Model for FRP Structures: Numerical and Experimental Analyses

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Abstract: The ability to numerically predict the ultimate strength of fibre reinforced polymer (FRP) structures is fundamental in order to enable design methodologies not resorting exclusively to experimental tests. In the last few decades, several authors have proposed failure initiation criteria for FRP materials. However, most of the proposed models are either limited in their application range (*e.g.* valid for unidirectional composites) or require layer-by-layer input data from experimental results that are very difficult to obtain (*e.g.* strength under biaxial loading). On the other hand, strength predictions based on first ply failure are overly conservative, especially for complex structures where local damage can occur without causing the overall structural collapse. Thereafter, in order to estimate the strength of FRP structures, damage progression models have been associated to failure initiation models. Some authors have adapted damage progression models developed for concrete materials, based on fracture energy. However, owing to the anisotropy and brittle nature of FRP materials, these models require extensive input data from various experimental tests, the values of which may vary widely for different FRP materials. Moreover, finite elements (FE) modelling of damage progression of FRP elements often involves layering the laminates and high computational costs. These limitations lead to the necessity of developing damage progression models able to capture the complex failure behaviour of FRPs while modeling the material as homogenous in order to reduce computational costs. In this paper, a new progressive failure model is proposed for the mesoscale modelling of homogenized FRP composites, considering failure initiation and damage evolution. The quadratic failure initiation model proposed uses two failure indexes, one for in-plane and the other for out-of-plane failure. The damage evolution model can be divided in two stages: (i) gradual stiffness loss, and (ii) final failure. In the first stage, the Matzenmiller-Lubliner-Taylor (MLT) exponential damage model is used, attributing different parameters for each elastic and shear moduli. In the second stage, a residual strength is attributed to each direction beyond a limit strain. The progressive failure model was implemented in the FE commercial package ABAQUS through a user material subroutine (UMAT). The results show that the proposed model is able to accurately predict the strength and failure modes of pultruded FRP structures under different loadings, by modeling the laminates as homogeneous orthotropic materials.

Keywords: Pultruded FRP material, FE model, Homogenization, Failure model, Damage.

1178 - Estimation of the Shear Strength of RC Members with Externally Bonded, Fully-Wrapped FRCM Composites

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Abstract: Externally bonded (EB) fiber reinforced cementitious matrix (FRCM) composites have been proven to be an effective solution for shear strengthening existing reinforced concrete (RC) members. Different layouts, namely U- and full-wrapping, of the EB composite can be adopted depending on the geometry and type of RC member. In the case of RC beams, the fully-wrapped layout is not always possible due to the presence of the slab. However, this layout is particularly attractive in the case of RC columns, where the composite can be applied easily and may provide significant strength increase. Although FRCM composites are attracting interest, the availability of analytical design models is still quite limited. In particular, few studies regarding the evaluation of the shear strength of FRCM fully-wrapped RC members are available in the literature. In this paper, an analytical model for the estimation of the contribution of fully-wrapped FRCM composites to the shear strength of RC members is proposed. The model is based on the truss analogy commonly adopted by various codes and guidelines for the estimation of the shear strength of RC beams and for fiber reinforced polymer (FRP) strengthened RC beams. The analytical model estimates the contribution of the FRCM to the member shear strength accounting for the bond behavior of the specific composite employed, which is an important aspect since FRCM composites have reported different bond behavior than FRP composites externally bonded to concrete substrates. The accuracy of the model provisions is assessed by comparing analytical and experimental results of RC beams fully-wrapped with a carbon FRCM composite.

Keywords. shear strength; analytical model; FRCM composites; fully-wrapped configuration.

1211 - A Discussion of Differences between Single-Lap Tests and Full-Scale Beam Tests in Terms of Frcm-Concrete Debonding

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Abstract: Fiber-reinforced cementitious matrix (FRCM) composites are a recent addition to the family of fiber-reinforced composites employed as externally-bonded reinforcement to strengthen reinforced concrete members. FRCM composites use a cementitious matrix rather than epoxy, which is typically used for the well-known fiber-reinforced polymer (FRP) composites. For both FRCM and FRP, the weakness of the technology is the premature debonding of the composites, which in most cases is a brittle phenomenon. The study of the debonding is often carried out at the small-scale level by employing small blocks of concrete with a strip of composite applied to one face. Different set-ups exist to study the phenomenon at the small scale. The most common set-up is the pull-push single-lap direct-shear test, in which the composite strip is pulled while the concrete block is restrained in such a way that the interfaces between the composite and the block is subjected mainly to shear stresses. The set-up is designed to represent the shear stress-transfer that occurs at the composite-concrete interface in full-scale strengthened beams.
Single-lap direct-shear tests are commonly used to study the debonding phenomenon because the specimens are easy to construct and handle, especially compared to full-scale beams. Nevertheless, the open question in the scientific community is whether the results of single-lap direct-shear tests can provide useful information on the debonding phenomenon in strengthened beams. This paper aims at providing an insight into this open question. The paper focuses on single-lap shear tests and full scale beam tests that employ a polyparaphenylene benzo-bisoxazole (PBO) FRCM composite.

Keywords. FRCM; bond; direct-shear tests; full-scale beams.

1228 - Maximum FRP Bar Diameter and Bar Spacing for Crack Control in Flexural Reinforced Concrete Members

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Abstract: During the design of reinforced concrete elements, satisfying serviceability limit state conditions is very important. To simplify the calculations of crack width, for the elements subjected to bending, the EN 1992-1-1 (2013.) gives a restriction of bar diameter or bar spacing which satisfy allowable crack width (tables 7.2(N) and 7.3(N)). During the last decades, FRP reinforcement became a good replacement for steel reinforcement, especially in an aggressive environment. Calculation methods for reinforced concrete elements with FRP bars (FRPRC) are developed from calculation methods for reinforced concrete elements with steel bars. Now, more and more, these rules are implemented in some national codes, and they will be implemented in Eurocodes soon. Procedures for the calculation of maximum bar diameter and bar spacing to control crack width are shown in the paper. These two values depend on each other and the focus of the paper is set on calculations of the bar diameter. Due to different modulus of elasticity between FRP and steel, the tables used for steel cannot be used for concrete beams reinforced with FRP bars. Therefore, the parametric calculations of maximum FRP bar diameter are described in this paper and new tables and diagrams are shown. The calculations were made according to rules from EN 1992-1-1 (2013.), paragraph 7.3.4 and equations (7.8) and (7.9) but instead of the material properties for steel reinforcement, those for FRP reinforcement are used. For additional explanations and considerations, EC2 Commentary (2008.) is used. Also, due to many types of FRP reinforcement, one table for different materials will not be sufficient. Therefore, for easier usage, diagrams for maximum value of bar diameter are developed and shown in the paper.

Keywords: FRP, reinforcement, cracks, bar diameter, bar spacing.

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1358 - Design of a Replacement Fibre-Reinforced Polymer Footbridge

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Abstract: Saxe Street footbridge is a new glass Fibre-Reinforced Polymer (FRP) footbridge designed by WSP on behalf of Balfour Beatty on a Design & Build contract with Network Rail. The new FRP footbridge replaces a wrought iron iron footbridge built in 1884 that was suffering from extensive corrosion.
The new bridge carries a footpath over the Great Western Railway line in Teignmouth (UK) and consists of a single 12.7m span simply supported deck made with pultruded FRP modular panels and connections and clad in moulded FRP panels. The design solution combined rapid and safe installation with a considerable reduction in future maintenance requirements that provided economic, operational and sustainability benefits.
This paper presents some of the challenges faced during the design stages. These challenges include understanding the effects of the material's behavior on the robustness and serviceability of the structure, together with its effects on the substructure and local site.
Site-specific challenges were encountered due to the lightweight nature and low stiffness of the new footbridge, linked to the structure's location over a railway and the stability of the existing substructure.
The new and old footbridges are shown in Fig. 1a and Fig. 1b respectively.

a) b)

Fig. 1. Saxe Street footbridge, a) new replacement FRP footbridge, b) old wrought iron footbridge.

Keywords: Fibre-reinforced polymer, FRP, footbridge, design, robustness, lightweight, buffeting, sustainability

1483 - Finite Element Modeling of Large Rupture Strain (LRS) FRP-Confined Concrete Columns

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Abstract: Extensive studies have demonstrated that confining a concrete column by large rupture strain fiber reinforced polymer (LRS FRP) composites can increase significantly its ultimate axial strength and ductility. For finite element analysis of such passively confined concrete columns by plasticity-based approaches, the plastic dilation angle must be quantified. For LRS-FRP confined concrete column, by increasing the lateral strain, the rate of confinement pressure is nonlinear compared to the linear rate provided by conventional FRPs (i.e., carbon FRP, glass FRP and aramid FRP), due to the bilinear tensile stress-strain nature of the LRS FRP material. This will cause the dilation behavior of LRS-FRP confined concrete to be substantially different from that of conventional FRP confined concrete columns.

This study uses the cyclic compression tests of LRS FRP-confined cylindrical concrete columns to understand how the nonlinear confinement pressure will affect the concrete loading paths in terms of the change in the plastic dilation angles. Axial and lateral plastic strains obtained in cyclic tests are used for quantifying the plastic dilation angle of the confined concrete. Compared to conventional FRPs, it is revealed that for LRS FRP confinement the plastic dilation angle decreases by a steeper rate as a function of confinement lateral stiffness ratio. Also, the plastic dilation angle shows a different style as a function of axial plastic strain. For LRS FRP confinement the peak of plastic dilation angle occurs around the axial plastic strain of 2% which is substantially larger than that of conventional FRP confinement. These observations are used to perform finite element (FE) analysis of LRS FRP-confined concrete columns based on the ABAQUS software. With the employment of the concrete damage plasticity model (CDPM), the FE model can predict successfully the axial stress-strain relationships of LRS FRP-confined concrete.

Keywords: Large rupture strain (LRS), FRP, confinement, finiate element modeling, plasticity

1494 - A 3d Plasticity Model for Concrete and Its Application to Concrete Under Non-Uniform FRP Confinement

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Abstract: Fiber-reinforced polymer (FRP)-confined concrete members have been attracting extensive research attention. The mechanical behavior of concrete under uniform FRP confinement, as is found in FRP-confined circular concrete columns under concentric compression, has been well understood and can be accurately predicted using existing theoretical models. However, the same cannot be said about concrete under non-uniform confinement, as is found in FRP-confined concrete members with a non-circular cross-section or subjected to eccentric compression. The major obstacle is the lack of an accurate constitutive model for concrete under non-uniform passive confinement. The existing analytical stress-strain models for FRP-confined concrete are essentially one-dimensional (1D) (i.e. the so-called design-oriented models) or two-dimensional (2D) (i.e. the so-called analysis-oriented models), and are therefore not directly applicable to concrete under non-uniform FRP confinement which requires three-dimensional (3D) stress and strain relationships. The conventional plasticity models, though having the ability to predict 3D stress-strain responses, have been developed to reflect the experimental behavior of concrete under active stresses, and are thus incapable of accurate prediction of the behavior of FRP-confined concrete. An improvement to such a conventional plasticity model is to embed an accurate 2D analysis-oriented analytical model for FRP-confined concrete into a 3D plasticity model, leading to an analytically augmented (AA) plasticity model. However, such a combination involves an inherent approximation in connecting the 2D response of the former with the 3D response of the latter, and as a result such an AA plasticity model is still inaccurate for concrete under substantially non-uniform FRP confinement. This paper first presents a new plasticity constitutive model for concrete developed by the authors, in which a novel potential surface is employed to accurately predict the 3D stress-strain behavior of concrete under non-uniform passive confinement. The model has been implemented with the general-purpose finite element package ABAQUS, and its performance is demonstrated through simulating the mechanical behavior of an FRP-confined elliptical concrete column under concentric compression.

Keywords: Concrete, FRP, Plasticity model, Non-uniform confinement, Passive confinement.

DURABILITY AND LONG-TERM PERFORMANCE

1096 - Externally Bonded CFRP Strengthened RC Slabs, Four Years of External Environment Exposure And Evaluation of The Load Carrying Capacity

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Abstract: The results of a four years research project on the long-term behaviour of RC slabs strengthened using Externally Bonded CFRP are here presented. The experimental tests simulate a strengthening intervention on the lateral cantilevers of highway concrete box-girder bridges. For this application, the CFRP is bonded to the top surface of the concrete below a layer of asphalt. Under these conditions, the operating temperature in the adhesive can reach high values which in combination with high loads can compromise the effectiveness of the strengthening system.
Two slabs strengthened using non-prestressed CFRP strips have been placed in an external environment under direct solar radiation, loaded, from August 2015 to September 2019, and continuously monitored. The results show that under an 8 cm asphalt layer a maximum adhesive temperature of approx. 40°C was achieved at the location of the test (Dübendorf - ZH- Switzerland). Moderately good behaviour has been observed during the entire testing period, even though a continuous increase of CFRP strain was measured. The strength of the slabs was evaluated in September 2019, tests exhibited excellent performance, which was not affected by the 4 years of environmental exposure.

Keywords: CFRP strengthening, Long-term behaviour, RC structures, bridges, durability

1101 - Hygrothermal Ageing of Pultruded GFRP Profiles: Experimental Study and Prediction Models

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Abstract: Research concerning the long-term behaviour of fibre reinforced polymer (FRP) composites in civil engineering applications is increasing, as key actors in this industry recognize the existence of many knowledge "gaps" that still need to be fulfilled. Several competing mechanisms may affect the durability of FRPs during exposure to hygrothermal ageing conditions, and in the specific case of pultruded glassfibre reinforced polymer (GFRP) profiles, comprehensive and validated data on their durability is still limited. The typically long service lives required for most structures together with the low frequency of routine inspection and maintenance operations in civil infrastructure enhance the importance of having reliable durability data and suitable prediction models for the long-term performance of these materials. This study presents results of an experimental and analytical study designed to investigate the effects of hygrothermal ageing on the durability and long-term performance of two commercial GFRP profiles made of two alternative resin systems – unsaturated polyester (UP) and vinylester (VE), both comprising the same fibre content and architecture. Test specimens of the two types of profiles were subjected to different ageing environments, namely immersion in demineralised and salt water at three different temperatures (20 °C, 40 °C, and 60 °C) and continuous condensation at 40 °C for up to two years, and were tested after a desorption period, thus including the potential property recovery after drying to constant mass due to the reversible nature of some of the physical degradation mechanisms. The performance of both profiles was analysed and compared regarding their mechanical response in tension and flexure after being subjected to hygrothermal ageing. The experimental data thus gathered were subsequently used to derive analytical models for the prediction of long-term effects and service life of pultruded GFRP profiles based on the Arrhenius law. This provided estimates for the retention of strength and moduli in tension and flexure, for both UP and VE pultruded GFRP profiles when exposed to different hygrothermal environments.

Keywords: Hygrothermal ageing, pultruded profiles, durability, Arrhenius prediction models.

1207 - Enhancement of Mechanical Properties of FRP Composites with Silica Nanoparticles

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Abstract: To enhance the mechanical behavior of fiber-reinforced polymers (FRPs), the epoxy and vinyl ester resin modified by silica nanoparticles at 1, 2, 3, and 4 weight percent (wt%) were investigated. Tests of fracture toughness were conducted, and scanning electron microscopy (SEM) of the fracture surface was proposed to identify the toughening mechanism. In addition, impregnated fiber roving made of modified resin was studied for improvements in tensile strength and stiffness. The addition of silica nanoparticles to epoxy and vinyl ester resin resulted in various promotions in their mechanical properties. The fracture toughness and impact strength of the epoxy resin in the presence of 3 wt% nanoparticles were increased by 12% and 49%, respectively, compared with the virgin epoxy resin. Furthermore, the corresponding of the vinyl resin with 3 wt% nanoparticles were 20% and 94%. SEM of the fracture surface displayed a relatively rough surface with tortuous cracks, thereby leading to higher fracture toughness of the modified resin system. The tensile strength of the impregnated basalt fiber roving made of the modified vinyl resin was obviously improved, and results showed that 18% promotion was obtained at a particle content of 3 wt%. In addition, the modified epoxy resin had less tensile strength enhancement to basalt fiber roving. Damage mechanisms of resin with nanoparticles were analyzed and differences due to the varying nanoparticle content identified.

Keywords: mechanical properties, fracture toughness, silica nanoparticles, impregnated roving

1214 - Durability and Lifetime Prediction of Flax Fiber Reinforced Polymer Composites

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Abstract: Flax fiber reinforced polymer (FFRP) composites are demonstrating promising outcomes which makes them potential candidates to replace synthetic composites in various industrial applications. However, there is limited information regarding their long-term performance, and it is usually acknowledged that natural fibers are less resistant than their synthetic counterparts. In this context, it is crucial to study their durability before considering their use for structural rehabilitation and strengthening in construction. This study aims to investigate and predict the performance of FFRP composites with a bio-based epoxy matrix. The test program consisted in exposing FFRP laminates and FFRP strengthened concrete slabs to different accelerated ageing conditions over a total period of 2 years, and with various combinations of temperature and relative humidity in the ranges 20-60°C and 50-100% RH, respectively. Series of tensile, short beam and pull-off tests were periodically performed on ageing samples in order to evaluate their property evolutions over exposure time in the various environments. Finally, collected experimental data were analyzed using statistical tools, in view of developing a degradation model and evaluating the service lifetime performance of this new bio-based composite.

Keywords: Lifetime prediction, flax fiber-reinforced polymer composites, accelerated and natural ageing, tensile strength, adhesive bond.

1323 - Three-Dimensional Characterization of Naturally Corroded Steel-Reinforced Concrete Using Computed Tomography

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Abstract: Understanding the corrosion mechanisms of reinforcement is essential for the design and retrofitting of durable concrete structures. Accurate detection of reinforcement corrosion is quite challenging; hence, the potential of a high-energy micro-computed tomography (μCT) imaging system is examined here to study the three-dimensional (3D) corrosion distribution and the associated concrete cracking. Little attention has been paid to investigating the natural corrosion of large concrete elements using μCT; thus, a bulky part of naturally corroded steel-reinforced concrete collected from a 50-year-old building was examined in this study. The obtained μCT images were processed and reconstructed into a three-dimensional (3D) model. Non-uniform reinforcement corrosion was detected as cracks exposed one side of the reinforcement resulting in excessive corrosion and cracking, yet only minor corrosion and concrete cracking occurred at the protected side of the reinforcement. The volume of the uncorroded portion of the 10M steel rebar was measured to estimate the corrosion level, and it was found that only one-third of its original size remained intact. The corrosion products detected through μCT were visually compared with the specimen, and an acceptable agreement was observed. However, due to the inhomogeneity of concrete materials and beam-hardening imaging artifacts, some small regions outside the corrosion zones were falsely captured along with the corrosion products. Based on the aforementioned results, it can be concluded that micro-computed tomography (μCT) has considerable potential for investigating the corrosion and cracking mechanisms of large reinforced concrete elements.

Keywords: 3D nondestructive characterization, Natural reinforcement corrosion, Reinforced Concrete, X-ray micro-computed tomography.

1333 - Characterisation of the Degradation Behaviour of a Loaded Vinyl Ester Gfrp Bar in Alkaline Concrete Environment

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Abstract: In recent years, fibre-reinforced polymers (FRP), and glass-fibre reinforced polymers (GFRP) in particular, are advocated to be a promising alternative to traditional steel reinforcement in concrete structures to alleviate corrosion-related problems. Despite a large amount of studies on the short-term performance of FRP as non-prestressed reinforcement in concrete structures, there exists a lack of methods and experimental data to predict the durability of FRP-reinforcement. The investigation of the long-term behaviour is very extensive and complex due to the high effort and the long test duration. Furthermore, the occurring degradation and failure mechanism of FRP reinforcement in the real installation situation are largely unknown.
This study investigates the degradation behaviour of a GFRP bar embedded in highly alkaline water-saturated concrete under sustained uniaxial load. The focus is to identify the relationships between material composition, existing material stress and occurring time-dependent and bar-specific degradation and failure mechanisms of GFRP bars in alkaline environments. The test setup is based on a creep rupture test according to the time-to-failure procedure, whereby the creep rupture and an alkali resistance test are combined into one comprehensive testing. Samples are conditioned at temperatures of 20, 40 or 60 °C to archive accelerated ageing effects and the stress level is varied. In order to analyse the occurring damage and failure mechanisms, one GFRP bar, that experienced creep-rupture during conditioning at 60 °C, is microscopely exanimated by Stereomicroscopy, and SEM/EDX.

Keywords: FRP internal reinforcement, long-term performance, sustained load effects, degradation behaviour, characterization of FRP and FRC materials/systems.

1384 - Durability of Sea Water Sea Sand Concrete Filled Filament Wounded FRP Tubes Under Seawater Condition

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Abstract: In order to reduce the amount of fresh water and river sand used for constructing conventional ordinary Portland cement (OPC)-based concrete, sea water sea sand concrete (SWSSC) can be used as an alternative to such concrete. To address the corrosion vulnerability of carbon steel reinforcement when used with SWSSC, using corrosion resistant materials, such as fibre reinforced polymers (FRPs) is recommended. This study investigates the durability of filament wounded FRP tubes when exposed to SWSSC as the inner environment and seawater as the outer environment. Glass, basalt and carbon FRP tubes were used to study the effect of fibre type. The mechanical properties in terms of the compressive and hoop tensile strengths of such tubes after exposure to SWSSC and seawater were investigated. Specimens were exposed to 90 days of SWSSC and seawater solutions. In order to study the temperature effect, ambient, 40 °C and 60 °C temperatures were used.

Keywords: Sea water sea sand concrete; FRP tubes; Filament winding; Durability; Corrosion

1426 - Microscopic and Durability Evaluation of In-situ Extracted Internal GFRP Reinforcing Bars after Temporal Exposure

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Abstract: This study assesses the durability of GFRP bars in concrete bridges exposed to a real-time weather environment. In order to observe any possible mechanical and chemical changes in the GFRP bars and concrete, several tests were conducted on the GFRP bars and surrounding concrete of the extracted cores. Carbonation depth, pH, and chlorides content were performed on the extracted concrete cores to evaluate the GFRP-surrounding environment and see how they influenced certain behaviors of GFRP bars. Scanning electron microscopy (SEM) was performed to observe any microstructural degradations within the GFRP bar and on the interfacial transition zone (ITZ). Energy dispersive spectroscopy (EDS) was applied to check for any chemical elemental changes. In addition, glass transition temperature (TA) and fiber content tests were carried out to assess the temperature state of the resin and check any loss in fiber content of the bar after these years of service. The results showed that there were no microstructural degradations in both bridges. EDS results were positive for one of the bridges, and they were negative with signs for leaching and alkali-hydrolysis attack on the other. Fiber content results for both bridges were within the permissible limits of ACI 440 standard. Carbonation depth was found only in one of the bridges. In addition, there were no signs for chlorides attack in concrete. This study adds new evidence to the validation of the long-term durability of GFRP bars as concrete reinforcing used in field applications.

Keywords: Glass fiber-reinforced polymer (GFRP), Durability, SEM, FTIR, EDS, TA, pH, chlorides content

1487 - A Machine Learning Approach to Modelling the Bond Strength of Adhesively Bonded Joints Under Water Immersion Condition

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Abstract: The durability of fibre-reinforced polymer (FRP)-strengthened structural elements has been subject of recent research. Despite a large number of experimental studies in this field, there is no comprehensive model to predict the performance of composite systems exposed to severe environmental conditions. This paper evaluates the durability of FRP-to-concrete joints by applying machine learning (ML)-based data-driven techniques. A comprehensive experimental database on the durability of FRP-bonded connections subjected to water immersion conditions is collected to develop ML models. Three approaches, namely multiple linear regression (MLR), artificial neural networks (ANN) and adaptive-neuro fuzzy inference system (ANFIS) are established to identify the shear bond strength based on the geometrical and mechanical properties and the environmental conditions. The performance of these methods is evaluated based on their accuracy in predicting the bond strength of FRP-to-concrete joints after exposure to water immersion conditions. A comparison of the results indicates that ANN outperforms other methods with reasonable accuracy in estimating bond strength. Moreover, the study on the effects of environmental factors demonstrates that the combination of moisture and elevated temperature highly impacts the bond capacity of the joints immersed in water. Finally, an equation is proposed as a function of geometrical, mechanical and environmental properties of the FRP-to-concrete connections which can be used for rapid assessment of the bond capacity in adhesively bonded joints.

Keywords: Fibre-reinforced polymer (FRP) composite; Long-term durability prediction; Bond; Machine learning.

FIRE, IMPACT AND BLAST LOADING

1085 - Ratio Between Protection Coefficients and Oversized Coefficients for Pultruded Elements in Fire

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Abstract: The main objective of the work presented is to provide a method to design the protection of pultruded elements in case of fire. The method is based on the development of tables similar to those already available for steel structures.
Using this table the designer will be able to calculate the protection to be given to each type of pultruded profile section based on its thickness and thermal conductivity. As a result it will be possible to obtain the specific over-dimensioning coefficient.
For the development of these tables, the maximum temperature restriction for class 4 sections has been applied, which is made in steel, but modified for pultruded sections based on the work carried out to date.
For this purpose, Eurocode 3 part 1-2 has been used to obtain the temperature in the section of each pultruded profile. Different properties of the pultruded material have been derived from experimental data carried out by other authors. Additionally, the mechanical properties and ultimate resistances of these profiles at different temperatures have also been obtained from previous literature.

Keywords: Pultruded elements, Fire protection, dimensioning method, class 4.

1090 - Residual Tensile Strength of Textile Reinforced Mortars After Have Been Exposed to Elevated Temperatures

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Abstract: The present paper demonstrates initial results from an ongoing experimental and analytical research programme on masonry structures confined with Textile Reinforced Mortars (TRMs). In the present experimental stage, three series of uniaxial tensile tests were conducted on TRM coupons having variables the types of fibres and the ambient temperature. The purpose of this experimental investigation is to examine the residual strength of Carbon, and Basalt fibre textiles, used for the preparation of TRMs, after having been exposed to elevated temperatures. Within the scope of the experimental programme, TRM coupons and single fibre yarns have been exposed to three different temperatures (1oo °C, 200 °C and 300 °C) before tensile testing. Subsequently, parts of all specimens were subjected to Scanning Electron Microscopy (SEM) to assess any changes in the microstructure, both of the mortar and the fibres. Dogbone specimens were used to test the TRMs in tension, while prismatic specimens were used to assess the mortar's flexural tensile and compressive strength. For each temperature group, additional tensile tests were conducted on bare fibre yarns to assess changes in their mechanical properties. A significant decrease in the compressive strength of mortar observed between 20 °C and 100 °C, while there was a tendency for that value to increase gradually from 100 °C to 300 °C.
On the other hand, the flexural strength increased between 20 °C and 100 °C and gradually started to decrease as the temperature rose to 300 °C. Overall, the residual strength of the TRMs, as the results indicated, decreased with temperature. Two main reasons are identified as responsible for that behaviour; loss of bonding between the fibres and the matrix and deterioration of the fibre's and the mortar's original strength. Moreover, changes in the porosity of the mortar and the fibre coating monitored with the use of Scan Electron Microscopy (SEM).

Keywords: TRMs, elevated temperatures, tensile tests.

1145 - Flexural Performance of NSM CFRP Strengthened Concrete Beams under Temperature

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Abstract: In the past two decades, the use of Near-Surface Mounted (NSM) Fibre Reinforced Polymer (FRP) strengthening technique has increased in the retrofitting of damaged structures such as buildings, bridges, storages, etc. In the NSM technique, epoxy resins are usually used as a bonding material and have an important effect on the bond performance between the FRP and concrete. Exposure of these resins to increment of temperatures (i.e. around or beyond the glass transition temperature, T_g) may lead to changes in their mechanical properties, so that the performance and effectiveness of the strengthening system can be affected.

In the present work, an experimental programme is performed to study the effect of temperature on the behaviour of NSM FRP strengthened RC beams. Unlike to most of the existing literature, where performance of the strengthening system under fire temperature was studied, the aim of this study is to consider a high ambient temperature (i.e. similar to temperature during the summer days). Six specimens have been tested up to failure in two different series. Each series includes a control beam and two NSM CFRP strengthened beams with two different areas of CFRP. In the first series, the specimens have been tested at room temperature, whilst those of second series have been tested at 40 ºC.

Results of the effect of temperature on the flexural response of strengthened RC beams with different NSM CFRP ratio are evaluated in terms of flexural performance, failure mode and bond performance along the FRP laminate. According to experimental results, the stiffness of specimens was not significantly affected by temperature. Besides, large laminate length avoided FRP debonding in strengthened specimens and CFRP rupture was the observed failure mode, irrespective of the testing temperature. Finally, bond resistance was assessed with available analytical procedure. Comparison between analytical predictions and experimental results confirm the procedure to be conservative, as no end debonding was neither predicted nor experimentally observed.

Keywords: NSM CFRP, Retrofitting System, Temperature, Experimental Study.

1164 - Influence of Elevated Temperatures on the Bond Behaviour of Sand-Coated and Ribbed GFRP Rebars in Concrete - Pull-Out Tests and Calibration of Temperaturedependent Bond Stress vs. Slip Laws

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Abstract: This paper presents experimental and numerical investigations on the bond between concrete and GFRP rebars at moderately elevated temperatures. Pull-out tests were performed on sand-coated and two types of ribbed rebars, embedded in concrete cylinders, from room temperature up to 300 °C. The specimens were first heated up to the predefined temperature (measured at the rebarconcrete interface) and then loaded up to failure. The applied load and the slip of the rebars at their free and loaded ends were measured during the tests. The results confirmed that both the bond strength and stiffness suffer significant reductions with temperature, and that the surface finishing and glass transition temperature of the rebars are determinant factors governing the GFRP-concrete interaction at elevated temperatures. Most of the bond strength of the ribbed rebars was degraded up to 250 ºC (well above the rebars' T_g), while in the sand coated rebars, such level of degradation occurred even before the T_g was attained. Using the experimental data obtained from the pull-out tests, local bond stress *vs.* slip laws were numerically calibrated considering the reduction of the bond strength, bond stiffness and elastic modulus of the rebars caused by increasing temperatures.

Keywords: GFRP rebars, elevated temperatures, bond, concrete, bond stress-slip laws.

1167 - Fire Behaviour of GFRP-Reinforced Concrete Slab Strips: Fire Resistance Tests And Numerical Simulation

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Abstract: This paper presents experimental and numerical investigations on the fire behaviour of GFRP-reinforced concrete (RC) slab strips. In the first part of this study fire resistance tests were performed on four concrete slab strips reinforced with sand-coated GFRP bars, in which the influence of the following parameters was assessed: (i) the concrete cover thickness; (ii) the presence of cold anchorages in the GFRP rebars, (iii) the presence of lap splices in the fire-exposed length and (iv) the concrete strength. The specimens were tested in a four-point bending configuration, being subjected to a sustained service load, while the bottom surface was exposed to the ISO 834 fire curve. These experiments were then complemented with the development of three dimensional (3D) thermo-mechanical finite element (FE) models of the slab strips to simulate the fire resistance tests. Both the temperature-dependent thermo-physical and mechanical properties of the constituent materials were considered; the GFRP-concrete interaction was also modelled by means of local bond *vs*. slip laws, which were previously calibrated by the authors for different temperatures. Comparisons between numerical and experimental results confirmed the accuracy of the FE models in predicting the thermo-mechanical response of GFRP-RC slab strips during fire exposure, namely in terms of temperatures, midspan deflection increase with time, failure modes and fire resistance. Both experimental and numerical results confirmed that (i) the fire resistance can be drastically reduced when the rebar splices are directly exposed to heat, and (ii) even adopting relatively small concrete cover thicknesses it is possible to attain considerable fire endurances provided that the anchors of the GFRP rebars remain sufficiently cold. Moreover, the specimen manufactured with a higher concrete strength presented less extensive cracking, reducing the localized heating of the reinforcement and leading to a higher fire resistance.

Keywords: GFRP-reinforced concrete; fire resistance tests; FE modelling, GFRP-concrete bond

1216 - Effects of Impactor Geometry on Pultruded Composites Under Low-Velocity Impact Loading

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Abstract: An experimental program on the drop-weight impact response of pultruded composites subjected to low-velocity impact loading was performed. The specimens were struck by impactors of various geometries in order to investigate the effects of geometric parameters on the damage evolution of such material. To minimize other parametric effects such as impact energies, impact velocities, and impactor masses, the specimens were subjected to a fixed impact energy level of 240J with a uniform impactor mass and a constant dropping height. The impact characteristics and performance acquired from the tests were compared to present the differences of impact response on the pultruded composites. Damage evaluation was introduced to compare the failure modes associated with the impact events. The results demonstrated that the extent of damage varies with respect to the change of the sharpness of the impactors. The impact performance in terms of maximum impact load and energy absorption ratio increases with the increase of the flatness of the impactor surfaces (initial contact area) whereas the contact duration decreases slightly with respect to the initial contact areas.

Keywords: Pultruded profiles, Geometry effects, Impact performance, Damage evaluation.

1465 - Temperature Effects on the Mechanical Properties of the GFRP Sheets

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Abstract: Glass fibre reinforced polymers (GFRP) have great potential to improve the performance of existing structures, but the resin used to bond the fibres in the composite is generally flammable and temperature sensitive that inhibit their application in the rehabilitation of structures. To better understand thermal behavior of the GFRP sheets, tensile tests were performed replicating field conditions as part of an extensive study on the effects of climate change on the performance of structures. Tests were conducted under two scenarios 1) specimens were subjected to a sustained temperature and then monotonically loaded to failure and 2) specimens were subjected to sustained constant tensile load or sustained constant deformation following which temperature was increased until the specimen failed. A sudden drop in the mechanical properties of the GFRP was observed as the temperature approached the glass transition temperature ". However, a stable level of mechanical properties, ~185 MPa tensile strength and ~16.5 GPa tensile modulus, maintained beyond until about 250°C due to the fibres' contribution in the composite in both scenarios. An analytical model was also developed to capture the mechanical properties of the GFRP under elevated temperatures. The elevated temperatures not only impacted the mechanical properties but also changed the failure mode of the composite from brittle to ductile with softer failure at high temperatures.

Keywords: Elevated temperature, analytical modelling, mechanical properties, GFRP, sustained load and tensile test.

1470 - A Novel Design Procedure for CFRP-Strengthened Concrete-Filled Steel Tubes to Resist Impact Loads

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Abstract: Concrete-filled steel tubes (CFSTs) have received growing attention, owing to their rapid construction, reduced labor requirement, and reasonable material cost. While in service, the CFSTs can be subjected to a variety of environmental and mechanical stressors, which make them vulnerable to subsequent loading events. Considering the high durability and strength-to-weight ratio of carbon fiber-reinforced polymer (CFRP), it has been used to enhance the structural response of the CFSTs under service loads. However, there is still a research gap regarding the response of CFRP-strengthened CFSTs subjected to lateral loads, such as vehicle collision, as well as water- and wind-borne debris impact. This motivation led to the development of a computational framework to evaluate the response of CFSTs with and without CFRP subjected to impact loads. In this study, a set of representative finite-element (FE) models supported by the experimental tests is developed for impact simulations. The response of the CFSTs is studied using a range of response measures, including internal forces and deflections, as well as the energy absorbed during impact. The investigation is further extended to a systematic effort on the influence of various design parameters related to CFRP, concrete, and steel tube. From the conducted investigations, the absorbed energy is identified as the critical parameter for such members' design under impact loads. A new procedure to design the CFRP-strengthened CFST beams subjected to impact loads is then proposed. The accuracy of the presented method is confirmed by comparing the absorbed energy from the section analysis to that from high-fidelity simulations. This study is concluded with a detailed example, illustrating the strengthening of CFSTs using CFRP sheets.

Keywords: CFRP, Concrete-Filled Steel Tube, Lateral Impact, Design Method, Absorbed Energy.

FRP AS INTERNAL REINFORCEMENT

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1028 - Compressive Behaviour of Glass Fiber-Reinforced Polymer (GFRP) Reinforced Concrete Columns

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Abstract: Fiber-reinforced polymer (FRP) bars offer several advantages over steel bars, including higher tensile strength, lighter weight, and non-corrosiveness. There is currently an increased use of FRP-reinforced concrete structures worldwide. However, due to the low compressive strength and modulus of FRP bars, current FRP design codes such as ACI 440.1R-15 and CSA S806-12, neglect the contribution of FRP bars to the ultimate compressive capacities of reinforced concrete columns. This study aims at investigating the feasibility of using glass FRP (GFRP) bars as internal reinforcement in concrete columns, subject to concentric and eccentric loading. A total of four 180 mm x 180 mm square RC columns with heights of 1000 mm and 1100 mm were tested, including two GFRP-RC columns and two steel-RC columns. One GFRP-RC column was tested under concentric loading, and the other was tested under eccentric loading at an eccentricity-to-width ratio of 44.4%. The two steel-RC columns were replicates of the two GFRP-RC columns, and served as control specimens. All columns were cast with normal strength concrete of 34 MPa compressive strength and had the same longitudinal reinforcement ratio of 2.48%. Steel ties of 10 mm diameter spaced at 180 mm were used as transverse reinforcements in all columns. The results showed that GFRP-RC columns had lower load-carrying capacities than their steel-RC counterparts under both concentric and eccentric loadings. The ultimate capacities of GFRP-RC columns were 22% and 34% lower than their steel-RC counterparts at concentric and eccentric loadings, respectively. Also, the GFRP- and steel-RC columns exhibited similar modes of failure, which were mainly compression-controlled with concrete cover spalling and concrete crushing, under the different loading conditions. No rupture or buckling of longitudinal bars was observed. The contribution of GFRP bars to the ultimate column capacity under concentric loading, was found to be around 10.5%. Therefore, this study recommends that the contribution of GFRP bars to the ultimate capacities of RC columns should not be ignored.

Keywords: Keywords: GFRP bars, columns, compression, concrete.

1044 - Behaviour of High-Strength Concrete Circular Columns Reinforced with GFRP Bars and Spirals under Simulated Seismic Loading

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Abstract: Circular reinforced concrete (RC) columns have many advantages compared to rectangular or square ones such as higher confinement efficiency and more appealing aesthetic appearance. The differences between the mechanical properties and behavior of FRP reinforcement with respect to steel include, but not limited to, the linear elastic behavior of FRP without yielding, lower strain capacity and different compressive and shear strengths. These properties significantly affect the response of FRP-RC columns as they directly affect confinement behavior. In addition, the seismic response and energy dissipation are greatly affected when FRP reinforcement is used. Therefore, developing independent code provisions for FRP-RC members is necessary. The experimental data available for FRP-RC circular columns under seismic loading, especially columns constructed with high-strength concrete (HSC), is very limited. Hence, the current provisions of the Canadian code for FRP-RC columns are very conservative, particularly for HSC, compared to those for steel-RC counterparts. In this study, two full-scale GFRP-RC circular columns were constructed and tested under a simultaneous seismic and axial loading. One specimen was constructed using HSC with 85 MPa concrete compressive strength, while normal-strength concrete (NSC) with 35 MPa was used for the other specimen as reference. Both test specimens had 350-mm diameter, 1,750-mm shear span, 1.2% longitudinal reinforcement ratio, with 85 mm spiral pitch. The results showed that the confinement requirements of the Canadian code for circular columns could be too conservative for NSC columns, while this is not the case for HSC ones, which need much more confinement reinforcement.

Keywords: Circular columns, GFRP bars, high strength concrete, seismic, spirals.

1047 - Toward a Practical Approach to Experimental Evaluation of Cracking Behaviour of GFRP-reinforced Concrete

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Abstract: The low modulus of elasticity and high tensile strength of Glass Fiber Reinforced Polymer (GFRP) reinforcing bars results in designs often governed by deflection and crack control at the serviceability limit state. Bond characteristics of GFRP bars – the manner and efficiency with which force is transferred to the bar from the surrounding concrete – significantly impacts the control of cracking provided by the bar. Unlike standardized steel reinforcing bars, GFRP bars are manufactured with a variety of surface preparations and conditions – each effecting bond. To address this in design, a bond coefficient – termed kb in this work – is adopted to normalize bond characteristics of different bars and permit the use of single design equations. This paper reports a pilot study of two simple test methods intended determine this coefficient. The ASTM D7913 pull-out test is suitable for rapidly determining relative values of kb. The non-standard prism tension test has the advantage of providing quantitative, in addition to qualitative comparison of cracking behaviour as it is affected by reinforcing bar type. The authors propose the evaluation of kb using ASTM D7913 but confirming the overall bond performance using a smaller number of prism tension tests. Preliminary results presented in this paper indicate that three of the four GFRP bars considered have better bond characteristics than the ASTM A615-compliant bars to which they were compared.

Keywords: bond coefficient, concrete, GFRP, crack width, pull-out test.

1089 - Development Length of GFRP Reinforcing Bars in Concrete Containing Seawater

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Abstract: As the world faces a growing problem of freshwater scarcity, the construction industry—which as a sector is among the largest consumers of freshwater globally, especially for concrete mixing, curing and cleaning must consider alternatives that can help solve the issues associated with water shortages while continuing to meet the construction industry's essential needs. In many cases, the same regions experiencing severe water shortages are in relatively close proximity to the sea or ocean; in these areas, the concrete industry potentially has access to a practically unlimited source of water which is currently not widely viewed as a viable option. Although the use of seawater in concrete can result in some minor changes in its fresh and hardened properties, one of the main long-term challenges is related to the high concentration of chlorides which leads to depassivation of reinforcing steel and results in corrosion-induced deterioration. Therefore, a corrosion-resistant reinforcing material, such as fiber-reinforced polymer (FRP) bars, may provide an acceptable alternative for concrete structures when non-potable mixing water is used. The present research is part of a broader study exploring the viability of seawater concrete structures reinforced with glass FRP (GFRP) bars. In this work, an experimental program comprised of six beam anchorage specimens reinforced with 16 mm spiral GFRP bars were tested. Three control beams were fabricated using concrete made with regular tap water, while the remaining beams used concrete made with seawater. The embedment length of the GFRP bars in the anchorage regions ranged from 300 to 500 mm. A method is proposed for calibrating theoretical bond-slip relationships using strain readings along the embedded region. Using the calibrated model, the development length of the bars is estimated and compared with current design codes which were found to be conservative. The results of this study, in combination with other results not presented here, suggest that the use of seawater as mixing water in concrete has a negligible effect on the bond behavior and overall structural performance of GFRP-reinforced concrete elements. Further research on long-term performance is ongoing.

Keywords: Concrete, GFRP, Seawater, Corrosion, Bond.

1091 - Behaviour of Columns Constructed with Internal FRP Reinforcement Under Axial Loading

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Abstract: The internal steel reinforcement in RC structures is susceptible to corrosion due to chemical attacks such as chloride induced corrosion and carbonation. Fibre Reinforced Polymers (FRP) have been studied in the field of civil/structural engineering and it composites the drawbacks connected with steel reinforcement. There are numerous experimental and numerical researches conducted on the use of FRP in flexural RC elements. However, there are insufficient number of studies conducted on the use of FRP reinforcement under compression in elements such as columns. This research examines the performance of RC columns fully internally reinforced with Glass FRP and tested under concentric load. Four half-scale reinforced concrete columns with dimensions of 130x130x1500 mm were fabricated and tested under compression load. One sample was longitudinally reinforced with steel bars acting as a reference, whilst the other three remaining samples were longitudinally reinforced with GFRP bars. The samples were instrumented with Strain Gauges (SGs) and Linear Variable Differential Transducers (LVDTs) in order to monitor the behaviour of the samples throughout the loading. The result suggests that the structural response of the steel and GFRP reinforced are highly comparable. All the samples failed because of buckling of the columns. The column reinforced with steel displayed 17% higher ultimate capacity compared to the columns reinforced with GFRP. In addition, the column reinforced with GFRP showed relatively higher deformability. The variation in the structural response of the steel and GFRP samples were relatively insignificant.

Keywords: Reinforced Concrete; Column; Corrosion; FRP; Compression.

1117 - Performance of T-Beams, Using GFRP Reinforced and Geopolymer Concrete

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Abstract: The key purpose of this paper is to present test results of incorporate recent developments in engineering and to analyse through a set of tests the structural response of T-section beams reinforced by pure GFRP bar beams with geopolymer concrete (GPC). The investigated parameters include the longitudinal reinforcement ratio and properties of GPC. The experimental results are discussed in terms of load-deflection relationship, width of cracks and modes of failure. In addition, the findings can be used to determine the applicability of the existing design requirements for estimating the load capacity of the beams.

Keywords: Geopolymer Concrete, Glass Fiber-Reinforced Polymer (GFRP) bars, T-Section Beam.

1175 - Behaviour of Square Concrete Columns Reinforced with Macro-Synthetic Fibres and GFRP Rebars under Axial Compression

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Abstract: The durability of reinforced concrete (RC) members reduce significantly under aggressive environmental conditions due to the corrosion of steel reinforcement. Also, corrosion of steel reinforcement in concrete members can drastically reduce their load-carrying capacity. The use of fibre-reinforced polymer (FRP) bars is an attractive alternative for steel reinforcement in RC members. However, their brittle failure nature due to the linear elastic stress-strain characteristics is a significant concern. The addition of discrete fibres in FRP reinforced RC members can improve the post-cracking behaviour and provide pseudo-ductility. This study aims to understand the behaviour of macro-synthetic poly-olefin (PO) fibre-reinforced RC columns with glass FRP (GFRP) rebar as internal reinforcement under pure compression. Eight RC columns of cross-section dimensions 305 mm × 305 mm were cast with GFRP rebars and different fibre dosages. The test matrix includes (i) control specimen with no fibres (ii) GFRP RC columns with 0.35% PO fibres (iii) GFRP RC columns with 0.70% PO fibres and (iv) GFRP RC columns with 1.0% PO fibres. Experimental results revealed that the macro synthetic fibre addition to FRP GFRP RC columns improves peak load carrying capacity under pure compression. Also, fibre addition improved the post-peak behaviour without undergoing a sudden drop in the load resistance. Sudden crushing of concrete in compression was prevented due to the presence of fibres which provided pseudo-ductility.

Keywords: Short columns, Axial compression, GFRP reinforcement, Macro-synthetic fibres.

1287 - Accuracy of Existing Theoretical Models on The Assessment of the Design Shear Capacity of Slender RC Beams with Steel and GFRP Rods without Transverse Reinforcement

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Abstract: The paper is devoted to the shear of slender concrete beams without transversal reinforcement flexurally reinforced with two types of reinforcement: steel and GFRP (glass fiber reinforced polymer). The research program included 29 single-span, simply supported T-section beams (b = 400 mm, b_w = 150 mm, h_f = 60 mm, h_{tot} = 400 mm) with the axis span of 1800 mm. The three point loaded beams (with the load located at a distance of 1100 mm from the support) had the shear span to depth ratio a/d in the range of 2.9-3.0 referring to the slender beams. The four times lower elasticity modulus of the GFRP reinforcement caused a gradual, progressive shear tension failure mode, opposite to the abrupt failure mode peculiar to the RC beams. The difference in the elasticity modulus of both types of reinforcement resulted in the increase in the shear capacity of the RC beams in the range between 30% and 66% comparing to the shear capacity of the GFRP reinforced beams with the same reinforcement ratio. The paper presents a comprehensive analysis of the test results in relation to the design shear capacity according to the selected theoretical models. The generalized assessment of computational analysis indicated that the predicted shear capacity values calculated according to selected models gave good agreement with the experimental results.

Keywords: shear, slender beams, T-cross section beams, GFRP, capacity, design models.

1329 - Tensile Tests at GFRP Rebars

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Abstract: Tensile testing seems to be a standard procedure for most engineering processes. There are standards for tensile testing for most materials including GFRP rebars. So it seems to be strange to see research relevance in such an well known and daily performed test. The authors will focus on the diameter influence and possible effects and influences of conclusions from non-perfect tensile tests.
There are several questions not yet answered sufficiently. As the modulus of the rebars can be calculated from the amount and the modulus of the fibres with high accuracy, the strength can not be calculated in a similar manner. In addition the diameter seems to have an influence even for the same laminate properties and qualities on the strength. The authors shows in a theoretical discussion as well as in practical tests that some common assumptions seem to be reconsidered. It is important to know that commonly accepted residual strength concept is questionable if the tensile strength cannot be determined to a high percentage of the “real” strength.
The discussion on that should encourage young as well as experienced researchers always to question standards and standard procedures, read scientific papers of adjacent disciplines and make their own thoughts and approaches.

Keywords: tensile test, composite rebar, failure mode.

1345 - Experimental Study on the Compression Behaviour of Concrete Column Reinforced with Steel-Frp Composite Bar

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Abstract: In order to study the compression behaviour of concrete columns reinforced with steel-FRP composite bar (SFCB), three groups (group one uses steel bars, group two uses BFRP bars and group three uses SFCB) of reinforced concrete columns were made and tested. The effects of the eccentricity and reinforcement type on the bearing capacity, deflection, crack and failure mode were analyzed. The results show that the larger the eccentricity, the larger the deformation at the middle of the SFCB concrete column, the larger the crack width and the lower the ultimate bearing capacity. Among the three types of reinforced concrete columns, for axial compression, the BFRP reinforced concrete columns show the highest bearing capacity, but for eccentric compression, the the reinforced concrete column exhibits the highest bearing capacity. The maximum deflection of SFCB concrete column deflection is 3 % larger than that of reinforced concrete column, but 24 % smaller than that of BFRP reinforced concrete column.

Keywords: steel-FRP composite bar, concrete column, compression performance, eccentricity, reinforcement type

1369 - Review of FRP Bar to Concrete Bond in Hygrothermal Conditions

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Abstract: Fibre-reinforced polymer (FRP) composite reinforcement is now commonly used as internal reinforcing bars for concrete structures subjected to aggressive environments where corrosion of steel reinforcement is likely. However, the FRP bar surface resin has been shown to deteriorate when exposed to aggressive environments and this can result in a significant loss of bond strength with the surrounding concrete. In this paper, a review of FRP bar pull-out tests is collated for the following hygrothermal conditions; full immersion in water, full immersion in alkaline solution, full immersion or wet-dry cycles in sea water solution, full immersion in acidic solution and freeze/thaw cycles in water or chemical solution. The durability of the bond behaviour is analysed in terms of influence of material properties, specimen geometry, and simulated environmental condition. The analysis has highlighted the large scatter that exists for experimental results between studies and seeks to explain this scatter through discussion of the impact of exposure to material properties and the importance of sound experimental design. Key knowledge gaps are identified that can be used to inform future studies.

Keywords: FRP bars, bond, concrete, durability.

1382 - Multiscale Reinforcement of Epoxy Composites with Glass Fibre and Carbon Nanotube

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Abstract: This paper presents an investigation on the modification of macro-scale fibre reinforcement with nano-scale filler to produce multiscale glass fibre reinforced polymer (GFRP) composites. Glass fibres were spray-coated with multi-walled carbon nanotube (MWCNT) aqueous suspension and were stacked together with epoxy binder to produce composite laminates by using hand lay-up method, followed by vacuum bagging. The stability of MWCNT aqueous suspension was analysed using zeta potential and UV-Vis and the distribution of MWCNT on the glass fibre was examined using scanning electron microscope. To evaluate the mechanical performance, flexural test and short beam test were performed. Improvement by 53.6% and 74.8% was observed in flexural strength of the 5-ply glass fibre (5GF) composites incorporated with 0.1 and 0.5 wt % of MWCNT, respectively. Meanwhile, flexural modulus of the same composites showed more than 20% improvement at both MWCNT concentrations. For interlaminar shear strength (ILSS), the highest improvement was found to be at 0.5 wt% of MWCNT which increased ILSS of the multiscale composite by 43.8% compared to the control sample (5GF). It is also interesting to note that 6-ply glass fibre (6GF) composite had lower flexural properties and ILSS in comparison to 4-ply glass fibre (4GF) and 5GF multiscale composites incorporated with MWCNT, indicating that we successfully reduced the weight of the GFRP composites by reducing the glass fibre ply but significantly enhanced their mechanical performance.

Keywords: Glass Fibre, Carbon Nanotube, Multiscale Composite, Flexural, Short Beam.

1400 - Modelling the Bond of GFRP Bar and Concrete for the Thermo-Mechanical Behaviour of RC Slabs

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Abstract: Present study aims to develop a 3D thermo-mechanical numerical model to better understand the influence of elevated temperature on the bond between the GFRP bars and concrete in RC structural elements. The relevant constitutive thermal and mechanical parameters of the bond were calibrated using experimental measurements, including pull-out tests under different elevated temperatures. The accuracy of the numerical thermo-mechanical predictions was first confirmed by pull-out test simulation, then the modelling strategy was transferred to RC thin slabs. Good accordance of experimental and numerically predicted temperature fields was followed by the verification of the complete methodology through comparison of experimental and numerical thermo-mechanical slabs' response. The relevant laboratory experimental measurements and observations confirmed the accuracy of the developed numerical modelling, emphasizing the importance of proper selection of material parameters and their temperature dependencies. This work contributes to the improvement of simulation strategies for GFRP RC structures in elevated temperature environments and tends to increase the confidence in adopting GFRP reinforcement bars in concrete design.
Keywords: GFRP bar, RC slab, bond, thermo-mechanical behaviour, finite element modelling.

1401 - The Influence of Reinforcement Ratio on the Shear Behaviour of Sand Coated Basalt FRP Bars reinforced beams

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Abstract: Qatar is known by its harsh corrosive environment that is represented by high periodical humidity, and dust accompanied by temperature fluctuation. Also, geographically Qatar is considered a peninsula, this in turn makes it highly susceptible to seawater spray which contains high chloride contents. Recently, basalt fiber reinforced polymer (BFRP) bars are among the most investigated types of anti-corrosive advanced composites in structures. Accordingly, the present paper aims at examining the efficiency of sand coated basalt fiber reinforced polymer (SBFRP) bars and ribbed glass (GFRP) stirrups in resisting shear stresses in large scale basalt fiber reinforced concrete (BFRC) beams. The effect of the reinforcement ratio r_f (2.054 ϱ_{fb} and 4.53 ϱ_{fb} where ϱ_{fb} is the balanced reinforcement ratio) on the shear capacity of the tested beams was investigated. Results revealed an increase in the ultimate load capacity by 48% when the reinforcement ratio was increased from 2.054 ϱ_{fb} to 4.53 ϱ_{fb}. Also, it was clearly noticed that the beam stiffness has significantly enhanced at higher reinforcement ratio, especially after the onset of first flexural crack.

Keywords: Sand coated BFRP bars, Ribbed GFRP stirrups, Corrosion, Shear strength, Stiffness.

1482 - Structural Behavior of Axially Loaded Geopolymer Concrete Sandwich Wall Panel Reinforced with BFRP Grids

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Abstract: A new type of precast concrete sandwich wall panel, consisting of two basalt fiber reinforced polymer (FRP) reinforced geopolymer concrete wythes and an insulation layer, which are connected with hollow tubular glass FRP connectors, is studied in this paper. Ten sandwich wall panels were prefabricated and subjected to concentric axial loading. The primary test variables included slenderness ratio of the wall panel, longitudinal spacing of connectors, and the ratio of the wythe thickness to the insulation layer thickness. The load-deflection relationships, failure modes, and load-strain relationships were carefully investigated. All the wall panels failed by crushing of concrete. The spacing of FRP connectors was found to have a marginal impact on the axial load capacity because of the existence of capping beams at the end of panels. A theoretical second-order analysis was performed to predict the ultimate axial load of equivalently assumed solid wall panels. The effective slenderness ratio of the sandwich wall panel was deduced from the comparison of the theoretically predicted results with the experimental ones.

Keywords: Precast sandwich panel, Geopolymer concrete, BFRP reinforcement, FRP connector, Axial loading.

HYBRID STRUCTURES OF FRP AND OTHER MATERIALS

1072 - Seismic Design Guideline for Hybrid GFRP-Steel RC Bridge Pier Considering Performance-Based Design

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Abstract: Glass Fiber Reinforced Polymer (GFRP) bars have been introduced in reinforced concrete (RC) structures to improve their performance against steel corrosion. However, the brittle failure, with no ductility provided of GFRP reinforcing bars is the main challenge limiting their use in many regions of high seismic activity. Especially in the critical sections, such as plastic hinge regions of a column. In this study, GFRP bars are used in conjunction with steel bars that are well-known for their ductile behavior, thus creating a hybrid section. The hybrid section includes exterior GFRP bars and interior steel bars. Two layers of transverse reinforcements, either made from GFRP (external cage) or steel (internal cage), are also provided. The prescribed hybrid section is one potential alternative to mitigate corrosion of steel reinforcement while maintaining adequate stiffness and ductility in the structure. In addition to the experimental work, the seismic behavior of hybrid sections is numerically investigated using validated fibre-based models. After model validation, a nonlinear incremental dynamic analysis will be performed to establish performance-based damage states, which are later utilized in the seismic fragility-based assessment of a bridge pier located in Vancouver, British Columbia. The damage states (i.e. minor, moderate, major, and local collapse) and the corresponding performance criteria (material strain and the associated drift values) are presented for the hybrid section.

Keywords: Hybrid reinforcement, Hybrid bridge piers, Performance-based design.

1088 - Influence of the Degree of Inclination of Applied Load on the Behaviour of Hybrid and FRP Elements

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Abstract: Steel Shear walls (SSW) are the common lateral resisting system around the world. Early stage research on utilising the beneficial properties of fibre reinforced polymers FRP to increase the strength and improve the behaviour of SSW systems is under way. The application of FRP in SSW systems merits review of the effect of this material on the behaviour of the connection between the hybrid steel/FRP infill plate and the boundary frame elements.
An investigation of the influence of the degree of inclination of applied load on the behaviour of Hybrid and FRP connection elements was undertaken for the main scope of this research. This is so as to fully understand the effect of the inclined load on Hybrid and pure FRP connection elements and understand the material behaviour under such load.
The Hybrid FRP/Steel and Pure FRP specimens were prepared using vacuum oven. 3 Hybrid GFRP/Steel, 3 Hybrid CFRP/Steel, 3 CFRP, 3 GFRP and 3 Steel specimens were prepared. The specimens size was kept constant of 120mm width and 510mm length. The infill steel plate of 0.8mm thickness was used in the Hybrid specimens. The hybrid specimens were made from 4 layers of FRP and infill plate. The pure FRP specimens were made from 7 layers.
The results of the tested samples showed that Hybrid/Steel GFRP and Pure CFRP has higher ultimate load and energy dissipation comparing to steel specimens. The Pure CFRP presented the highest ultimate load and energy dissipation than the rest of the specimens. After normalization by weight it was seen that CFRP performed the best in Energy dissipation and Ultimate load, giving the highest values. The Hybrid/steel GFRP Ultimate Load and Energy dissipation higher than Pure GFRP.

Keywords: FRP, shear walls, infill plates, connections.

1092 - Structural Performances of Composite Pultruded GFRP Emergency Structures

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Abstract: The use of composite FRP pultruded elements in civil constructions is nowadays widely accepted as a valid alternative to classic materials. In the case of emergency applications (as for temporary shelter after earthquakes, floods and all disastrous), the lightness, ease of transport, assembly, safety of use, possibility of disassembly and reuse are key aspects that composite FRP structures can provide easily.
This paper presents a design-to-testing-to-production process of a full-scale pultruded glass fiber reinforced polymer (FRP) structure to investigate the structural performances according to the design at ultimate and serviceability limit states by cyclic and monotonic loads up to the failure. The capacity of the composite structure was assessed with respect to instantaneous and time-dependent loading effects.
The experimental results are compared with the predictions of a numerical model based on the experimental mechanical characterization of the materials and the substructure such as frame elements and connections. The results indicate that the high performances of the structure provide a very good capacity in view of facing service loads and also in extreme conditions.

Keywords: Emergency structures, Pultrusion, Full-scale experimental testing, Composite structures

1196 - Compressive Behavior of Circular Sawdust-Reinforced Ice-Filled Large Rupture Strain Fiber-Reinforced Polymer Tubular Short Columns

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Abstract: The low temperature restricts the use of concrete in cold regions. As a building material since ancient times, the local ice might be a good substitute for concrete. In order to take full advantages of ice and to overcome its shortcomings, sawdust-reinforced ice-filled large rupture strain (LRS) fiber-reinforced polymer (FRP) tubular (SFLFT) column is innovatively developed in this paper, which holds great potential to serve as a compression member in cold areas. It is composed of an external LRS FRP tube filled with sawdust-reinforced ice. This paper presents an investigation on the axial compressive behavior of circular SFLFT short columns. A total of nine circular short columns, including three unconfined sawdust-reinforced ice specimens and six SFLFT specimens, were axially loaded to demonstrate the concept of the proposed novel columns. The main test variable was the number of FRP layers in the LRS FRP tubes. Test results indicated that the typical failure mode of SFLFT specimens is the hoop rupture of LRS FRP tubes near the mid-height region. The axial stress vs. strain responses of the LRS FRP-confined sawdust-reinforced ice exhibited an approximately bilinear shape. Both the compressive strength and the peak axial strain of the confined ice were approximately linearly increased with the increasing number of LRS FRP layers. A stress vs. strain model was proposed to evaluate the stress vs. strain response of confined sawdust-reinforced ice with reasonable accuracy

Keywords: FRP, Large rupture strain (LRS), Sawdust, Ice, Axial compression, Stress vs. strain model.

1361 - Feasibility of Bolted Connectors In Hybrid FRP-Steel Structures

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Abstract: Due to the low weight and excellent durability of composite materials, Fibre Reinforced Polymer (FRP) decks mounted on steel superstructures are becoming all the more common in engineering practice. Bolted joints are generally used to facilitate connections between an FRP deck and steel girders in road bridges. The connections are subjected to both high magnitude static forces as well as fatigue loading due to overpassing vehicles. With ever increasing traffic on both road and railway bridges, fatigue performance is of critical concern. Bolted FRP joints have been extensively researched in the past under static loading, but less is known about the fatigue and creep behaviour of such joints. Furthermore, little research exists on non-pultruded FRP profiles connected using bolted connections. Therefore, the objective of this research is to investigate connectors' feasibility by means of static, fatigue and creep experiments on four different types of bolted joints comprising mechanical connectors and injection techniques. The study focuses on application in vacuum infused GFRP panels with integrated webs made of multi-directional laminates) connected to steel bridge superstructures. In addition, experimental results are validated by Finite Element Analyses (FEA). Based on the obtained results, the novel injected steel-reinforced resin (iSRR) connector developed at TU Delft shows promising potential in hybrid steel-FRP bridges where good fatigue endurance of the connection and local loads in FRP panel, are required

Keywords: Bolted connections, non-slip connections, fatigue performance, combined short- and long-term loading; injected steel reinforced resin.

1457 - Application of Steel and FRP Reinforcement Combination in Moment Resisting Frames: Prospects and Challenges

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Abstract: The demand for seismic resilient communities is the main driving force behind efforts of research engineers to develop novel reinforced concrete (RC) structures with superior seismic performance. Post-earthquake damage observations raise concerns about the behavior of conventional steel bars in seismic resisting structural systems which are susceptible to large residual deformations after surviving seismic events. Therefore, for the last two decades, considerable efforts have been made to find alternative reinforcement materials such as fiber reinforced polymers (FRP) and to develop various concepts for the adoption of these materials to enhance the seismic resiliency of RC structures. One of these concepts is the combination of both steel and FRP bars in seismic resisting structures. Herein, this paper discusses the seismic performance of steel-FRP reinforced concrete moment resisting frames (SFRC-MRFs) with the aim to determine the prospects and existing challenges of this new system. This paper starts with brief discussion about lateral performance of SFRC beam-column joints and then investigates the cyclic behavior of SFRC-MRFs. Afterward, the feasibility of using FRP bars with predefined surface texture details to avoid undesirable failure modes in SFRC-MRFs under severe earthquakes is discussed. Finally, existing research gaps and challenges are determined to facilitate the future adoption of the SFRC-MRFs.

Keywords: Moment resisting frame, Seismic, Steel-FRP reinforcement, Damage-control

1479 - Behaviour of Filament Wound FRP-Rubberised Concrete-Steel Hybrid Double Skin Tubular Column (Hybrid RuDSTC) Under Axial Loading

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Abstract: Hybrid double-skin tubular column formed by three different materials namely fiber reinforced polymer (FRP) tube, concrete, and steel, is the new age column that is gaining popularity due to its high axial capacity, excellent corrosion resistance, and improved ductility. Filament wound FRP tubes are considered as a potential construction material by the researchers which offer both longitudinal and lateral strength. The use of rubberised concrete as the sandwiched material is a new concept that will make this column a potentially viable sustainable structural column. This paper focuses on the behavior of stub hybrid RuDSTCs composed of filament wound FRP, rubberized concrete, and steel under compression loading. The parameters are different rubber replacement ratios and outer FRP tube types. Results of this investigation show that hybrid RuDSTC has excellent ductility with a reasonable strength reduction due to the use of rubberised concrete which can be optimized for real-life applications in seismic prone areas and as mining infrastructure.

Keywords: Filament wound, FRP, rubberised concrete, hybrid RuDSTC, axial loading.

1491 - Shear Performance of BFRP Reinforced Geopolymer Concrete One-Way Slab

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Abstract: A combined use of basalt fiber reinforced polymer (BFRP) reinforcement and geopolymer concrete was adopted in one-way slabs to achieve improved durability and environmental friendliness. In total six BFRP reinforced geopolymer concrete one-way slabs were fabricated and their shear performance was evaluated through four points loading tests. The test parameters were concrete strength (30, 40 and 50 MPa) and reinforcement ratio (1.20% and 2.18%). The load-deflection relationships, crack patterns, failure modes and load-strain relationships of all the specimens were carefully investigated. Furthermore, two dimensional (2D) finite element (FE) analysis was conducted to reproduce the test results. The results obtained in this study indicated that: (1) the specimens were governed by shear-compression or diagonal tension failure depending on the reinforcement ratio but with similar shear resistance; (2) the shear resistance could be predicted with reasonable accuracy by existing design guidelines (e.g., JSCE guidelines) for FRP-reinforced concrete members; and (3) the FE model with implementation of appropriate material models provided a good prediction of the structural performance of the tested slabs with the implementation of constitutive laws for geopolymer concrete.

Keywords: One-way slab; geopolymer concrete; basalt fiber reinforced polymer; shear resistance; finite element analysis.

MATERIALS AND PRODUCTS

1139 - Modelling the High Strain Rate Tensile Behavior of Steel Fiber Reinforced Concrete Using Artificial Neural Network Approach

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Abstract: Conventional concrete material shows relatively low ductility and energy dissipation capacity under high strain rate tensile loads. The use of steel fibers into concrete can significantly improve the tensile behavior of concrete subjected to high strain rate loads by fibers bridging the concrete crack surfaces, resulting in a high impact resistance and energy dissipation capacity. Experimental research evidenced that the parameters of volume fraction, aspect ratio and tensile strength of steel fibers affect the characteristics of steel fiber reinforced concrete (SFRC) composite materials under high strain rate tensile loads. However, the existing design codes, i.e. CEB-*fib* model code 1990 and *fib* model code 2010, recommend design formulations for the prediction of the behavior of normal concrete under different strain rate loads, which are only function of strain rate of the loads. Accordingly, development of the design models to predict the behavior of SFRC materials when subjected to high strain rate loads is still lacking in the literature. Hence, the current paper aims to improve the design models recommended in the existing design codes (e.g. *fib* model code 2010). An artificial neural network approach is adopted to predict more accurately the tensile behavior of SFRC materials. Besides the strain rate load effect, this approach considers the effects of the volume fraction, aspect ratio and tensile strength of steel fibers. Finally, the predictive performance of the proposed model was evaluated by simulating relevant experimental tests.

Keywords: Steel fiber reinforced concrete, high strain rate load, analytical model, artificial neural network.

1171 - Optimising CFRP Recycling via Arrhenius-Type Kinetic Behaviour Analysis

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Abstract: Pyrolysis method is one of the promising methods which can be used for reclaiming of clean carbon fibres from CFRP composites. To further improve this recycling method, kinetic behaviour of CFRP decomposition needs to be investigated. By monitoring and analysing the weight loss of CFRP during thermal degradation, the activation energy (E) of composites is determined by Arrhenius-type model-free (Friedman method) and curve fitting methods (Coats-Redfern method). Results show that the decomposition of the CFRP is a complex two-stage reaction. During the first stage, approximately 75% of epoxy matrix is removed. In this stage, pyrolysis of composite remains efficient up to around 425 where above 55% of resin is removed. Within this temperature range, analysis of kinetic energy confirms that a higher conversion rate and lower activation energy can be achieved by using lower heating rate. The outcomes contribute to optimisation of design parameters and development of highly efficient and cost effective CFRP recycling method using pyrolysis technique.

Keywords: CFRP recycling. Pyrolysis. Thermal degradation. Activation energy. Arrhenius-type kinetic behaviour.

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1377 - Frp Bridges in the Flanders Region: Experiences from the C-Bridge Project

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Abstract: Currently, the number of fibre reinforced composite bridges in the Flanders region of Belgium is limited to a handful. These limited achievements are largely due to poor knowledge of clients (public and private), project managers, design engineers and contractors, which makes this option either unknown or still viewed with a certain degree of suspicion. In addition, there are no standards at Belgian or European level for the design of such constructions. The C-bridge project (roadmap into design, guidelines and execution of composite bridges in Flanders) aims to stimulate the design, the realization and the construction of composite bridges in Flanders by providing the necessary knowledge to the construction sector in the most suitable form. This knowledge will allow the awarding authorities and contractors to be able to make informed choices regarding fibre reinforced polymer bridges, but also offer the possibility to various Flemish companies to make the necessary transformation to this new and promising material. The paper presents results from the C-bridge project including a state of the art report, an analysis of the selection, cost determination and project specifications in Flanders, an overview of structural analysis and calculation methods, and a case study related to a recently built fibre reinforced composite bridge in Flanders. The results are helpful for the acceptance of fibre reinforced composite bridges as an alternative to timber, steel or concrete bridges, in Flanders and internationally.

Keywords: FRP, Bridges, Roadmap, Case study

1378 - Influence of the Stacking Angle on the Strength and Stiffness Properties of Tiled Laminates for Civil Applications: A Dic Based Approach

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Abstract: Tiled Composites (TC) are a bio-inspired oblique layered material, composed of stacking individual plies in a tiled fashion and joining them together with a polymer to form a rigid structural material. This concept has great potential in different sectors (i.e. bridge building, offshore construction, ship building, lock gates, fire resistance panels, ...) as it allows the manufacturing of composite plates from tiled strips of fabric which opens up the door for robotised production of panels of any shape and size. Because this is a relatively new concept, less is known about the mechanical properties of the material such as the strength, the local and global stiffness and the fracture mechanics properties. Further, the classic laminate theory does not fully describe Tiled Laminates (TL) as opposed to plane-parallel laminates and international literature is virtually non-existent. Although numerical finite element (FE) models are available, experimental data is needed to validate, calibrate and corroborate these models. In previous research, the longitudinal stiffness was described by strain gauges and extensometers, leading to scatter/variation in the results due to the specific location of the measurement equipment on the laminate, which cannot be justified by the FE models. This paper studies the full strain field in a TL under uniaxial tension by digital image correlation (DIC) and compares the results to the numerical FE models. Furthermore the influence of the stacking angle and laminate lay-up will be assessed. As a guidance for the uniaxial tensile tests, ASTM D3039 was used even though the specimens are not symmetric or balanced as prescribed by this standard. The results show that the strains along a path in the FE models on the top and bottom of the TL show large variations and that the peak values at the free edges in the FE models need to be averaged out over a relatively large distance. Further, the stacking angle and laminate lay-up have a significant influence on the stress distribution along the specimen and the failure mechanism. Finally, the tests allow for good local and global stiffness characterisation of a TL and will make it possible to establish a set of verified material parameters for the considered TL composites, which will serve as an input to the verification of the FE models.

Keywords: Tiled laminate, FRP composite, DIC, FEM

1383 - Black Ink-Facilitated Dispersion of Multi-walled Carbon Nanotubes and Fabrication of MWCNT/Glass Fibre/Epoxy Hybrid Composites

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Abstract: Maintaining, and preferably improving, the structural integrity of glass fibre-reinforced composites based on thermosetting epoxy matrices are of significant interest in a wide range of applications including civil infrastructure. The application of nanoscale reinforcements to the surface of the fibres to improve mechanical interaction with the matrix has gained considerable attention in recent years. In the present study, commercial black ink was used as dispersing agent to disperse pristine multi-walled carbon nanotubes (MWCNTs) in deionised water. The MWCNT solution was deposited onto to glass fibre (GF)/epoxy via two different methods: spreading and spraying. The MWCNT loadings, together with the dispersion methods implemented, affected the properties of the composites fabricated. The spreading method was found to be more effective than the spraying method. The flexural strength of the hybrid composite with 0.6 vol % MWCNT loading (CNT0.6) was boosted to 268 and 219% of the 3GF and 4GF values, respectively. The storage modulus of CNT0.6 was increased by 24% compared to 4GF.

Keywords: Fibres, Mechanical Properties, Morphology, Thermal Properties, Composites.

1406 - Experimental Study on the Mechanical Properties of a Novel Composite Anchorage System for CFRP Tendons

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Abstract: The composite-type anchorage, which combines the advantages of the mechanical-type and bonded-type anchorages, is expected to be a promising anchorage system for superior FRP tendons. This paper investigates the mechanical properties of a novel composite anchorage system for CFRP tendons. To examine the static and long-term mechanical properties of this novel anchorage system, a series of experimental studies were performed. The failure mode, load-carrying capacity, anchoring efficiency and creep behavior of the composite anchorage were investigated. The effects of pre-tightening force and grouted material on the anchorage performance were also examined. The results show that the novel composite anchorage system exhibited a satisfactory anchorage efficiency above 0.95 with an enhancement in load-carry capacity by 60.4%. Anchorage performance did not always positively correlate with the increasing of sand dosage in the grouted material. The optimum dosage of sand should not exceed 10%. Besides, the creep slippage of the novel composite anchorage under sustained load increased with the rising ambient temperature. The novel composite anchorage system experienced small creep slippage at normal temperature under high stress levels. This study provides insights into the mechanical properties of the newly developed composite anchorage, which will be beneficial to provide guidance for its future development and practical application.

Keywords: composite anchorage, CFRP tendon, experimental study, mechanical properties, creep behavior.

1467 - The Re-Use of End-Of-Life Fiber Reinforced Polymer Composites in Construction

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Abstract: In order to achieve a more resource-efficient society and a future with reduced carbon dioxide emissions, new technological challenges must be dealt. One way to reach a more sustainable world is to start re-using end-of-life structures and waste and give them a 'Second Life" with new functions in the society. As fiber reinforced polymer (FRP) composites are lightweight, strong, stiff and durable materials, there is great potential to re-use decommissioned FRP structures for new resource-efficient solutions in the building and infrastructure sectors. The present paper investigates innovative solutions in re-using wind turbine blades and glass fibre reinforced polymer (GFRP) pipes as structural elements in new bicycle and pedestrian bridges. Specifically, a concept design for decking system made of GFRP pipes is developed and discussed. The main design requirements for pedestrian bridges are considered and assumptions regarding end-of-life GFRP quality and their mechanical properties have been addressed. The aim of this paper is to contribute to a sustainable use of GFRP waste and at the same time provide a more cost-effective solution for short span pedestrian bridges. In a larger perspective, the authors would like to highlight the economically profitable potential of recovering and reusing / re-manufacturing end-of-life GFRP composites.

Keywords: Circular economy, sustainability, wind turbine, pedestrian bridge, FRP, recycling.

1477 - Influence Of Processing Conditions on the Mechanical Behavior of Mineral-Impregnated Carbon-Fiber (Mcf) Made With Geopolymer

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Abstract: Mineral-impregnated carbon-fiber (MCF) composites are for the construction industry a promising alternative to steel reinforcement or conventional fiber-reinforced polymer (FRP) composites due to their high mechanical performance over a wide temperature range, corrosion resistance, and high technological flexibility. For an efficient industrial fabrication of MCF, a long-range processing window need to be secured for the reactive impregnation suspensions. In this regard geopolymers offer great potential since - similar to organic thermosettings - they require thermal curing to accelerate polymerization, enabling quickly high early strengths.

To this end, the presented article is envisaged to study the impact of curing regimes and processing technology on the microstructure and mechanical properties of MCF. The MCFs were fabricated automated and continuously with a geopolymer-suspension and subsequently treated at elevated temperatures. Moreover, a helical winding was applied around the freshly pultruded bundle to profile the reinforcement surface, increase its "green" strength and handleability as well as its subsequent bond behavior towards concrete matrices.

The produced samples were thermally "activated" at 75 °C for up to 8 h only, to promote the geopolymerization process. With prolonged curing, a gradual increase in flexural and tensile properties was observed, confirmed by microscopic analyses showing a more reacted matrix microstructure with 8 h of curing time. The applied helical winding yielded a slight decrease in flexural performance, but densified the matrix microstructure of the MCF, proven by mercury intrusion porosity measurements. Finally, uniaxial tensile tests presented that the mechanical properties of such produced MCF reinforcements are in the same range as conventional FRPs.

Keywords: Carbon-fiber composite, Mineral impregnation, Geopolymer, Automated processing.

SEISMIC RETROFIT OF STRUCTURES

1012 - Tensile Behavior of Large Diameter Carbon Fiber Anchors

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Abstract: The use of carbon fiber (CF) anchors is becoming more common in structural retrofit applications. Typically, CF anchors are used to prevent or delay debonding of fiber-reinforced polymer (FRP) laminates from concrete substrates, as in flexural strengthening applications. For seismic repair of reinforced concrete (RC) circular bridge columns, the role of CF anchors is typically to transfer large tensile forces from the column to adjoining members such as a footing or cap beam. Thus, the required CF anchor diameter should be large enough to resist the demand. The research presented in this paper focuses on the tensile behavior of 25 mm-diameter CF anchors to investigate the potential of large diameter CF anchors for seismic repair of RC circular bridge columns. To that end, the behavior of large diameter CF anchors was experimentally investigated through a number of pull tests to identify the impact of fan angle on the tensile rupture capacity. A unique test setup was designed and manufactured to test large diameter CF anchors. Based on the results of this study on commercially available 25 mm-diameter CF anchors, a 530 mm long fan with fan angle between 37 to 57 degrees is recommended with a dowel embedment depth of 380 mm. When the anchor fan is well-confined with a transverse CFRP wrap a tensile capacity of 250 kN is achievable.

Keywords: Carbon Fiber Anchor, Fan Angle, Pull Tests, Efficiency.

1026 - Determination of a Large-Diameter Carbon Fiber Anchor Capacity

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Abstract: The use of fiber-reinforced polymer (FRP) materials has become a key to enhancing the performance of existing structural elements. Debonding is a common failure mode when FRP sheets are used for the flexural or shear strengthening of reinforced concrete (RC) members. Anchoring the end of FRP sheets with carbon fiber (CF)-reinforced spike anchors, which are typically small, is a proposed method to prevent or delay debonding failure. In the case of seismic strengthening or repair, large-diameter CF anchors are required due to the high demand on structural members. Given the limited available data on large-diameter CF anchors, a challenge in this field is the use of large-diameter CF anchors for conventional RC structures exposed to seismic events. Thus, a testing program was developed to examine the behavior of large-diameter CF anchors. The behavior of CF anchors was examined via a pull-out test for various fanning angles ranging from 45° to 60°. The obtained test data for a given fan angle can be used to enhance the performance of RC structural members in terms of resisting seismic events.

Keywords: Carbon Fiber Anchor, Seismic Repair, Fan Angle

1058 - Seismic and Durability Assessment of Externally Bonded FRP Retrofits in Reinforced Concrete Structures after 2018 Anchorage, AK Earthquake

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Abstract: Externally bonded fiber-reinforced polymer (EBFRP) composites are a cost-effective material used for repair and seismic retrofit of existing concrete structures. Even though EBFRP composites have been extensively utilized over the past 20 years as seismic retrofits, there are few data documenting their performance in a real shaking event or after long-term use on concrete structures. In this study, semi-destructive and non-destructive techniques were employed to evaluate the performance and durability of EBFRP-retrofitted buildings that had experienced the 2018 Cook Inlet Earthquake in Anchorage, AK. The performance of EBFRP was evaluated and documented through photographic evidence. Acoustic sounding, infrared thermography, and bond pull-off tests were utilized to evaluate the quality of bonding between the EBFRP and concrete. EBFRP samples were also collected from building interiors and exteriors for chemical and thermal analysis to evaluate the long-term effects of environmental exposure. Although environmental conditions were found to influence the bond quality between the EBFRP composite and concrete substrate, no major signs of earthquake damage to the building components retrofitted with EBFRP were noted. Materials characterization results demonstrated no evidence of polymer matrix degradation in exterior EBFRP samples.

Keywords: EBFRP retrofit; seismic; deterioration; reconnaissance; durability; materials characterization.

1093 - Retrofit of Damaged RC Columns Using CFRP Jackets

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Abstract: This paper presents results of an experimental program undertaken to investigate the possibility of application of carbon fiber reinforced polymer (CFRP) jackets to reduce the risk of rebar buckling of axially loaded RC columns with circular or rectangular cross-section. Ten RC columns with height of 300 mm and three different cross-sections, i.e. circular of 150 mm diameter, and square of 100 mm and 150 mm side, with two ratios of stirrup spacing to longitudinal bar diameter, i.e. 7.6 and 11.7, are tested. Scaling of 1/3 was followed in general, also in the rebar diameter and the concrete mix. The specimens, after being tested under axial compression up to failure, were strengthened with CFRP jackets using wet lay-up process. The number of CFRP layers used in the jacket was determined in relation to the degree of damage the columns had suffered according to a damage scale that is introduced. The results of this work are encouraging towards the potential of using CFRP jackets in RC columns with sparsely spaced stirrups, both for strengthening of intact RC columns and also as a retrofit technique for RC columns with buckled longitudinal bars, e.g. after the event of an earthquake. This application may be extremely helpful for the retrofit of RC columns in earthquake prone areas in buildings that were not designed according to the modern code principles and therefore their stirrups are sparsely spaced.

Keywords: CFRP, RC columns, repair, rebar buckling, axial strength.

1229 - Seismic Retrofitting Clay Brick Masonry with Visco-Elasto-Plastic Adhesive Bonded CFRP Strips: Efficient Utilization of CFRP Laminates without Significantly Damaging the Substrate.

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Abstract: In the past decades, a range of strengthening techniques have been developed for enhancing the out-of-plane performance of unreinforced masonry walls. One technique involves the use of fibre-reinforced polymer (FRP) composites. Traditionally, stiff adhesives are used to bond the CFRP strips to the masonry. This can lead to an underutilization of the added CFRP strips due to intermediate cracking of the masonry. Five years ago an idea was developed to replace the conventional stiff adhesive, with a novel viscoelastic adhesive. This paper provides an overview of the research, from idea to practical application. Through a series of bending test on reinforced clay brick wallettes, it was shown that by using a visco-elasto-plastic epoxy instead a conventional stiff adhesive, a significant increase in terms of ductility and maximum withstandable load is reached and critical crack development is prevented. The deep mounted technique was accordingly developed where deeper grooves are cut in the masonry, after which FRP strips are installed in the center of the wall. The FRP strips therefore offer additional out-of-plane flexural strength to the wall for both out-of-plane loading directions whilst only installing the reinforcement from one side of the wall, leading to cost-effective retrofitting. The following step in the research was assessing the high-speed pullout behavior of deep-mounted CFRP strips bonded with a viscoelastic adhesive to clay brick masonry by means of direct pull-out experiments. Using the developed global bond-slip law as part of a partial-interaction analysis resulted in a good fit with the experimental results. The results were compared to previous direct pull-tests found in literature, showing that the application of a viscoelastic adhesive results in higher interfacial fracture energy and higher debonding slip. The next step in the experimental campaign showed that the deep mounting using a flexible adhesive did not lead to a degradation of the in-plane strength. Additionally, combing the proposed retrofit system with a single sided FRCM overlay increased the shear capacity with 80%, compared to the unstrengthened control specimens. The last step in the experimental campaign was calibrating the developed out-of-plane mechanical model through a series of full-scale high-speed cyclic out-of-plane experiments on retrofitted clay brick walls.

Keywords: Seismic, CFRP, retrofit, masonry, strengthening.

1239 - Backbone Curves of FRP Confined Concrete Columns for Nonlinear Analysis

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Abstract: Existing reinforced concrete (RC) columns that do not conform to current seismic detailing requirements carry the risk of non-ductile failure that can lead to catastrophic failure of the structure. The behavior of such non-ductile columns can be significantly improved by FRP jacketing to enhance the plastic hinges performance and shear strength of the columns, achieve ductile behavior of the structure, and minimize the potential collapse risk.

This paper presents the results for dynamic full-scale tests performed of square RC columns retrofitted with FRP jacketing. The externally applied FRP was utilized at the anticipated plastic hinge location. Seven full-scale columns, five of which were retrofitted with FRP jacketing and two benchmark columns without retrofit, were tested under simultaneous axial and cyclic lateral loads. The results of these tests demonstrate the significant improvement of the lateral displacement and energy dissipation capacities of the retrofitted columns.

The paper also describes the methodology used to construct backbone curves that were utilized to predict the theoretical seismic performance of the retrofitted columns. The proposed method follows the principles of the backbone curve development approach in ASCE/SEI 41-17 by employing sectional analysis to define key points on the nonlinear response curves of the columns. The experimental results of columns tested in this research program indicate that the proposed methodology produces backbone curves that compare well with the column response measured during the full-scale tests.

Keywords: Seismic Retrofit, Backbone Curves, Plastic Hinge, Column Retrofit, FRP, Plastic Rotation.

1263 - Cyclic Tests on Masonry Vaults Strengthened through Composite Reinforced Mortar: The Role of the Connection with the Abutments

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Abstract: Experimental cyclic tests on full-scale, isolated vaults, carrying their self-weight and subjected to a uniformly distributed transversal load were performed so to investigate on the effectiveness of the Composite Reinforced Mortar strengthening technique. It is based on the application, at the vault extrados or intrados, of a 30 mm thick mortar coating with Glass Fiber-Reinforced Polymer meshes embedded. In the tests, the reinforced layer was connected to the masonry abutments through steel bars and GFRP elements. The actual performances of these connections in preventing slides and uplifts at the spring sections, which reduce the strengthening effectiveness, are analyzed in the paper. The comparisons of the results with previous experimental tests (without connection at the abutments) and numerical simulations, evidence a good effectiveness of the strengthening intervention, with significant benefits in both resistance and displacement capacities, and permit to assess the actual effectiveness of the tested connection strategy.

Keywords: masonry, seismic retrofitting, composite materials, vaults, experimental tests

1379 - Seismic Performance of CFRP Jacketed Sub-standard RC Columns under High Axial Stress and Shear Demand

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Abstract: In the last decades, lessons learnt from the major earthquakes, that occurred in many countries, brought revisions in prevailing seismic design codes. As a consequence of this phenomenon, the current building stock in Turkey is mainly comprised of reinforced concrete (RC) buildings which were designed according to different seismic design codes. The presented paper is a component of a comprehensive investigation which containing three variables i) high axial load ratio defined as axial load divided by the axial capacity, ii) high shear demand defined as the ratio of shear demand at flexural yielding to shear resistance and iii) low transverse reinforcement ratio owing to large spacing among steel reinforcements. Thus, a total of four full-scale square RC columns comprised of i) one column designed to comply with the former Turkish Seismic Design Code (TSDC, 1975) and ii) three columns which are not compliant to any design codes (referred as sub-standard), were tested under high axial load ratio, 0.4 for code-conforming and 0.75 for sub-standard columns, combined with reversed cyclic lateral loading. The columns were also designed to have high shear demand in the order of 0.62 and 0.80 for bare sub-standard according to ACI 318 (2019) and TBEC (2018) design codes as sometimes observed in existing sub-standard structures. In addition to that, the ratio of shear demand for the code-conforming column is calculated 0.43 and 0.50 as per design codes, respectively. Besides, the ratio of transverse reinforcement area to the minimum required transverse reinforcement area was 0.19 and 0.77 for sub-standard columns according to ACI 318 (2019) and TBEC (2018), respectively. For the code-conforming column, the aforementioned ratio was 0.57 and 1.32 for both design codes, in the same manner. One of the sub-standard columns was kept as a reference column while the other two of them have been externally jacketed with one layer or two layers of carbon fiber-reinforced polymer (CFRP) sheets. Test results pointed out that the confinement provided by CFRP jacketing has remarkably improved the performance of seismically-deficient RC columns subjected to high axial compression under high shear demand in terms of lateral load capacity and ductility. The experimental results were also supplemented with theoretical work to evaluate the effects of CFRP jacketing on the seismic behavior of sub-standard RC columns.

Keywords: CFRP, Column, Retrofitting, Seismic, Sub-standard.

1435 - Elasto-Plastic Behavior on Seismic Retrofitting for Circular Steel Bridge Pier by Externally Bonded Carbon Fiber Sheets

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Abstract: In this study, the retrofitting effect of carbon fiber (CF) sheet wrapping method on circular steel piers subjected to cyclic loading was evaluated quantitatively using finite element analysis. To verify the accuracy of the finite element analysis model, the analytical results were compared with the experimental results obtained from the previous study. The circular steel specimen was subjected to an axial force equivalent to 10% of yield axial force and a gradually increasing cyclic horizontal load at the top of the specimen. Two retrofitting method were considered, first is the wrapping of seven layers of CF sheet before the loading of the specimen (reinforced specimen) and the latter is the wrapping of CF sheets after the specimen has undergone ultimate failure (repaired specimen). For the finite element analysis model, the column specimen was modeled as 4-node shell elements while CF sheet was modeled as 2-node truss elements. The validity of the analysis model was verified by considering the appropriate constitutive law for the steel specimen and by investigating the mode of application of the vertical loading. For the CF sheet elements, the capacity to resist compressive forces and presence of initial stresses were considered. The results showed that the reinforcement model can quantitatively evaluate the horizontal loading capacity and the buckling mode. For the repaired model, the horizontal loading capacity can be approximately evaluated as well, but is limited to the range where the horizontal displacement is small

Keywords: carbon fiber sheet, circular steel bridge pier, rehabilitation, buckling, finite element analysis

1493 - Effectiveness of U-wrap Anchorage of Flexural CFRP Reinforcement in Strengthened Reinforced Concrete Beams

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Abstract: Externally bonded carbon fiber-reinforced polymer (CFRP) composites have been instrumental in the flexural strengthening of concrete structures because of their high strength-to-weight ratio, corrosion resistance, rapid and easy installation, and reduced cost compared to complete or partial component replacement. However, a governing failure mode in most externally bonded CFRP applications is debonding from the concrete substrate, which limits the composite strength utilization and deformability. Improved performance, in terms of both deformability and ultimate strength, may be achieved with the addition of transverse U-wrap anchorage for longitudinally oriented CFRP tension reinforcement. Design guidance for U-wrap anchorage is, however, lacking due to the limited experimental data. This work reports on flexural test results from structural-scale reinforced concrete beams strengthened in flexure with externally bonded CFRP anchored with U-wraps. The parameter of interest is the ratio of the areas of U-wrap anchorage to flexural CFRP, which is varied between 3.2 and 9.6. Experiments employ a 3D digital image correlation (DIC) system to collect full-field displacement data that can accurately characterize the effects of U-wrap anchorage on the strain in the flexural CFRP as well as the failure origin and progression. U-wrap anchorage resulted in an increase in CFRP strain at ultimate flexural capacity of up to 68% with a corresponding increase in moment capacity and a change in failure mode. However, varying the ratio of the areas of U-wrap anchorage to flexural CFRP from 3.2 to 9.6 had little apparent effect on the flexural capacity of the beam.

Keywords: CFRP, strengthening, repair, anchorage, bond, reinforced concrete.

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1495 - Seismic Performance of Substandard RC Columns Retrofitted with Sprayed GFRM

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Abstract: There is a myriad amount of substandard reinforced concrete (RC) buildings in developing countries that do not comply with the requirements and instructions of the current building design codes. In particular, columns in these substandard buildings demonstrate unsatisfactory and undesired behavior against lateral loads, mainly due to low concrete compressive strength and poor reinforcement detailing. The problem is exacerbated when the axial load ratio (ratio of applied axial load to the axial load capacity) and/or the shear ratio (ratio of shear force corresponding to moment capacity (V_e) to the shear capacity (V_r)) is/are high, leading to brittle failure modes. In this study, three full-scale substandard RC columns subjected to high axial load ratio of 0.75 were tested under constant axial load combined with reversed cyclic lateral displacements. Shear ratio (V_e/V_r) of the substandard columns were 0.75 and 0.82 according to ACI 318-19 (2019) and Turkish Building Earthquake Code (TBEC 2018), respectively. According to the TBEC (2018), columns had a high $V_e/(f_{ctm}bd)$ ratio of 1.12, where, f_{ctm}, b, and d are the direct tensile strength of concrete, width of the cross-section, and effective depth of the section. The ratio of transverse reinforcement to minimum required transverse reinforcement according to the ACI 318-19 (2019) and TBEC (2018) was 0.19 and 0.77, respectively. Two of the columns were retrofitted with an innovative, cost-effective, and easily-applicable strengthening method, through external jacketing with sprayed glass fiber reinforced mortar (GFRM) of different characteristics. The remaining column was tested as the reference specimen to evaluate the efficiency of the strengthening method. The test results demonstrated the extremely poor performance of the reference substandard column as well as the remarkable lateral load capacity and ductility improvement provided by the adopted novel strengthening approach.

Keywords: Basalt mesh, GFRM, Reinforced concrete column, Seismic, Strengthening.

STRENGTHENING OF CONCRETE, STEEL, MASONRY AND TIMBER STRUCTURES

1007 - Analytical Model for Predicting the Torsional Capacity of Thin Walled Tubular RC Beams Strengthened with NSM CFRP Laminates

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Abstract: An analytical model to predict the torsional moment capacity and the type of failure of thin walled tubular reinforced concrete elements strengthened with near surface mounted (NSM) carbon fiber reinforced pol-ymer (CFRP) laminates is proposed. The model implements the thin walled space truss analogy, which forms the basis of current design codes, and eval-uates the torsional capacity as a combination of the resistance offered by the transverse steel reinforcement and CFRP laminate reinforcement. The contri-bution of the steel reinforcement is limited by its yield strength and that of the CFRP laminates by an effective maximum strain. The model also implements the modified compressive field theory to evaluate the concrete compressive strut inclination.
The predictive performance of the developed model is compared against available models and assessed against experimental data obtained within the current research project and available in the literature. The model predicts the failure type and the ultimate torsional capacity with an error of 2.4% (with Co.V. of 5.1%) for current experimental research and 7.2% (with Co.V. of 8.6%) for other literature data.

Keywords: Torsional strengthening, near surface mounted (NSM), carbon fi-ber reinforced polymers (CFRP), analytical model, space truss analogy.

1033 - Structural Behavior of Disturbed Regions in RC Beams Strengthened with NSM Steel Bars and Externally Bonded GFRP

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Abstract: Anchorage of externally bonded FRP sheets is gaining a lot of attention recently to improve the performance of strengthened concrete members. In this study, the use of GFRP U-wraps and flexural GFRP sheets is examined with and without the use of GFRP anchors. Eccentrically loaded high strength concrete beams introduce a disturbed shear region that is evaluated experimentally and analytically. The beam specimens are strengthened with different strengthening schemes, and the behavior of these beams are compared to each other experimentally. Moreover, a new analysis method is developed to predict the capacity of RC beams with and without strengthening. The method utilizes the truss analogy approach that is extended from the strut-and-tie model for unstrengthened beams. The new method is able to predict the capacity of the beam specimens at the key points (yielding and ultimate). Comparison of the analytical and experimental results are made. Very good agreement is found.

Keywords: Truss analogy, GFRP sheets, anchorage system, GFRP splay anchors.

1037 - Effect of FRP Bar Type on the Behaviour of Shear-strengthened Reinforced Concrete T-beams

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Abstract: This paper presents experimental and numerical investigations on the behaviour of reinforced concrete (RC) T-beams strengthened in shear with deep embedment (DE) fibre reinforced polymer (FRP) bars. The tests were carried out on an unstrengthened beam as well as two beams strengthened in shear with embedded glass FRP (GFRP) or carbon FRP (CFRP) bars. The gain in shear strength increased by 28.1 kN (37.2%) with the increase in FRP elastic modulus from 46 to 130 GPa, demonstrating the important influence of DE FRP bar elastic modulus on the shear strength enhancement. The DE CFRP strengthened beam had higher post-cracking stiffness than both the unstrengthened control beam and the DE GFRP strengthened beam. A finite element (FE) model was developed and validated. A FE parametric study involving beams nominally identical to the tested beams revealed that an increase in steel-to-FRP shear reinforcement ratio instigates a decrease in shear strength enhancement.

Keywords: Beams, Deep embedment, FRP, Reinforced Concrete, Shear strengthening.

1048 - Hybrid Anchors in Reinforced Concrete Slabs Strengthened with FRP sheets

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Abstract: Reinforced concrete (RC) slabs strengthened with carbon fibre reinforced polymer (CFRP) and subjected to flexural actions may experience many types of failure, including FRP debonding, FRP rupture and concrete crushing. Of these different types of failure modes, FRP debonding stands out as the most predominant type of failure because of its dependence on the relatively weak bond interface between the soffit of the RC member and the FRP sheet attached to it. Many anchorage systems have been developed to enhance the performance of strengthened systems, one of which is the hybrid anchor, which combines the effects of patch anchors and spike anchors. Hybrid anchors have shown significant enhancement when used with RC members subjected to shear forces. This study explores the effectiveness of hybrid anchors in slabs subjected to flexural actions. This study reports an experimental program in which four slabs were subjected to 6-point bending tests. The results show improvement in the maximum load at failure and a significant improvement in ductility.

Keywords: Carbon fibre, Patch anchors, Spike anchors, FRP anchors, Flexural strengthening.

1056 - Adhesively Bonded FRP Composites for Strengthening of RC Structures: Recent Advances

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Abstract: Bonding fiber reinforced polymer (FRP) composites to reinforced concrete (RC) structures has been accepted as a structurally-effective and cost-efficient strengthening and repair method. Research and development on this technique started in the 1970s and a great deal of effort has been made to study different behavioral aspects of FRP bonded concrete structures ever since, whose results have been reflected in several design codes and guidelines. Despite the extensive research, there is still knowledge gaps limiting the application of FRP materials in infrastructure. Long-term performance and uncertainty related to environmental durability and poor structural behavior at elevated temperature are among the most critical barriers. There are also issues related to debonding and how to increase the strengthening effect by means of using prestressed FRP laminates. This paper presents a review of the most recent works on FRP bonded RC structures related to abovementioned aspects conducted by different research groups in Sweden, Italy, and UAE.

Keywords: Fiber reinforced polymer (FRP); Strengthening; Steel; Debonding; Long-term performance.

1057 - Experimental Study of Slender Concrete Columns Strengthened with Longitudinal FRP Laminates and FRP Wrapping System

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Abstract: Strengthening of concrete columns with fiber-reinforced polymer (FRP) wrapping is a very well-known and effective method of strengthening whose function is increasing the confinement of the column. However, the wrapping method for eccentrically loaded concrete columns was not recognized to be as effective as its effect on the concentrically loaded columns. The additional eccentricity causes bending moment which may cause tension in one side of the column while wrapping has its best performance where there is uniform pressure from concrete to wrapping. For slender columns, the effect of eccentricity is even more critical since it is combined with the secondary moment effects. For slender columns, a solution is required to increase the flexural stiffness. Therefore, this study investigates the effects of longitudinal FRP laminates which are supported by FRP wrapping (to prevent buckling of longitudinal FRP laminates) on the strengthening of slender concrete columns using experimental large-scale testing. The tests include three slender concrete columns with length of 3048 mm and a diameter of 260 mm (slenderness ratio of 47) were considered as control (without strengthening), wrapped (only wrapping in hoop direction), and hybrid (wrapping and longitudinal FRPs). The columns were tested under eccentric axial compression loading until failure. The results showed a capacity gain of 44% for the hybrid system in comparison with the wrapping system of strengthening.

Keywords: Slender, Concrete Columns, FRP, Strengthening, Experimental Test.

1069 - Fibre Reinforced Mortar (FRM) for in Plane Strengthening of Masonry Panels

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Abstract: The effectiveness of Fibre Reinforced Cementitious Mortar (FRCM) as strengthening technique of masonry structures under seismic actions has been widely investigated by means of diagonal compression tests in the last decade. The results showed that the effectiveness of FCRM solution, based on the use of FRP grid embedded in mortar matrix, to increase the masonry walls shear capacity strongly depends on the axial stiffness of mesh reinforcement and on the mechanical properties of the matrix. The paper presents preliminary experimental results of tests carried out on specimens strengthened with a new strengthening solution based on the use of Fibre Reinforced Mortar (FRM) without the use of FRP grid. In particular, the strengthening system consists of an innovative high performance and high ductility mortar made by a mix of fibres spread in lime-based powder. The experimental program aims at investigating the soundness of such technique to increase the shear capacity of different masonry panels. In particular, the system was applied over limestone masonry walls with irregular texture, typical of existing buildings in Central Italy, and old-type clay brick masonry panels with regular texture, typical of existing buildings in the Northern Italy.
Keywords: Fibre reinforced mortar, FRM, diagonal compression tests, existing masonry buildings.

1079 - The Effectiveness of CFRP Ropes to Anchor FRP Shear-Strengthened RC T-Beams with Continuous Sheets

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Abstract: This study investigates the effect of CFRP ropes to anchor FRP shear-strengthened beams with U-wrap continuous sheets. The experimental program includes seven identical simply supported reinforced concrete T-beams tested under three-point loading. The steel stirrups are spaced at 220 mm along a shear span of 880 mm. The beams are divided into two groups based on the anchorage technique used. Group A represents FRP shear-strengthened beams with single, double and triple layers of U-wrap sheets and anchored using CFRP ropes. Group B includes specimens with single layer of CFRP sheets and anchored using the NSM, FRP extension, and horizontal FRP anchorage techniques. The experimental program tested a strengthened beam with no anchorage (EB) as a benchmark. The results of the experimental tests are presented in terms of ultimate load-carrying capacities, failure modes, and load-deflection relationships. The applied load versus strain relationships for the steel stirrups, and CFRP sheets are also investigated. The experimental results showed that the FRP rope anchorage technique is a promising solution to enhance the FRP shear contribution.
Keywords: RC beams; Fibre-reinforced polymers, Shear-strengthening; Anchorage; CFRP ropes.

1110 - Mechanical Performances of FRCM Shear-Strengthened Reinforced Concrete Beams: Experimental and Theoretical Investigation

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Abstract: In this paper, the mechanical behavior of reinforced concrete beams strengthened in shear with SRG (Steel Reinforced Grout) jackets is analyzed. An experimental investigation is carried out on 7 reinforced concrete beams strengthened in shear by U-shaped SRG (Steel Reinforced Grout) strips. The varied parameters were: the strengthening configuration (continuous and discontinuous), the distance between U-shaped strips and, the number of SRG layers.
To predict the shear capacity of SRG shear strengthened reinforced concrete beams, an analytical model found based on the Ritter–Morsch criteria failure was proposed. The model was developed through a best fit analysis of experimental results available in the literature collected in a database.
A numerical model based on a Finite Element procedure developed through Abaqus CAE 6.12 was also proposed. The procedure based on a macro-model approach, allowed to analyze the non-linear structural behavior of the SRG strengthened reinforced concrete beams. A cohesive model and a bi-linear local bond-slip law were adopted in the model to simulate the behavior at the SRG-to-concrete interface.
Predictions of the analytical and numerical models were compared with experimental results obtained by the above-mentioned tests.

Keywords: SRG, shear strengthening, reinforced concrete, beams.

1116 - Effect of Fabric Reinforced Cementitious Mortar (FRCM) on the Strength of Shear-Damaged Reinforced Concrete Beams

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Abstract: This paper discusses an experimental study on the shear strengthening of damaged reinforced concrete beams using fabric reinforced cementitious mortar (FRCM). The key parameters studied were: 1) level of damage, namely presence of the first shear crack and 70% of the ultimate theoretical load and 2) the wrapping scheme used (continuously wrapped and intermittent strips). In total six 2 m long rectangular beams were constructed, one of the beams was left unstrengthened to act as control specimen, while all of the remaining beams were wrapped using a U-shaped wrapping scheme. Two beams were strengthened prior to any loading and the remaining three beams were repaired after sustaining the specified damage. When comparing the two wrapping schemes, it was found that, while both were able to increase the load-carrying capacity of the beams, specimens with intermittent wrapping had about 88% of the capacity compared to fully wrapped beams. It was also found that both wrapping schemes were fully effective in restoring the beams' strength for the lower level of damage. However, as the damage increased the strengthening became less effective.

Keywords: Concrete Repair and strengthening, Shear, Damage, Fabric reinforced cementitious mortar, Textile reinforced mortar

1071 - Near Surface Mounted Technique for Strengthening Continuous RC Beams with FRP Bars

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Abstract: Continuous beams are preferred for reinforced concrete (RC) uniform girder bridges and buildings locating in high seismic risk; they increase the structural integrity and rigidity. However, because of the mechanical deterioration of RC structures, these continuous beams precisely require repair or strengthening either in order to increase their service life or to enhance their loading and deformation capacity. The main objective of the present research is to conduct experimental work in order to investigate potential of the FRP rods (CFRP and GFRP) for strengthening continuous reinforced concrete beams under flexural loading by using the Near Surface Mounted (NSM) technique. Thus, four large- scale continuous two-span beams were loaded up to failure, including one control beam and three beams strengthened internally with CFRP/GFRP bars in the sagging and hogging regions. The test results showed that implementation the NSM-FRP bars could significantly improve the load carrying capacity of continuous RC beam, while the failure mode was primarily affected by the strengthening length.

Keywords: FRP bars, continuous RC beam, strengthening, flexural behaviour.

1125 - Theoretical Prediction of Axial Response of FRP Fully/partially Confined Circular Concrete under Axial Loading

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Abstract: The present study is dedicated to develop a new axial stress-strain model for FRP-based confinement strategies in case of FRP fully/partially confined circular concrete columns under axial compressive loading. For calculating axial stress versus axial strain curve, a new formulation as a function of concrete dilation response was suggested based on a large database of test results of FRP confined concrete. A new methodology was also developed to predict the ultimate condition of partially FRP confined concrete to take into account the possibility of concrete crushing failure mode. To evaluate the reliability and predictive performance of the developed model, it was compared with experimental data available in the literature. The results showed that it is sufficiently capable of predicting the experimental counterparts with the reasonable precision in the design content. This model can be adopted not only for fully confined concrete, but also in case of partial confinement system, demonstrating its wide applicability.

Keywords: FRP Confined Concrete, Partial Confinement, Concrete Dilation, Axial Behavior.

1137 - Measurement and Analysis of Cracking Behaviour of RC Beams Strengthened with NSM CFRP Strips Using Digital Image Correlation

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Abstract: Near-Surface Mounted (NSM) Fibre Reinforced Polymer (FRP) technique has been proved to be an effective method to strengthen Reinforced Concrete (RC) flexural elements. At present there is a lack of provisions for predicting crack width, and the number of experimental data regarding crack width and pattern is still scarce for NSM FRP RC flexural members.
This paper presents the preliminary results of an extensive experimental programme aiming at studying the effect of different reinforcement arrangements on crack distribution on NSM Carbon-FRP (CFRP) RC beams. For this purpose, one RC beam and seven RC beams strengthened with different configurations of NSM CFRP strips were tested under a 4-point bending configuration up to failure. A pure bending span of 1100 mm was left in order to obtain a significant number of flexural cracks. Crack patterns were registered with a Digital Image Correlation (DIC) system that allowed obtaining the evolution of all cracks appearing in the pure bending span. Two user subroutines were developed so as to automate the procedure of measuring crack spacing and crack width along the height of the beam and during the test. The effect of dimensions, amount and geometrical distribution of the CFRP reinforcement on crack width and crack spacing were analysed and discussed. In general, it was found that NSM CFRP strengthening provided a reduction of crack width and crack spacing. Moreover, crack width decreased with the increase of the NSM CFRP reinforcement ratio. Finally, no significant effect of the groove distribution was detected.

Keywords: Crack Width, NSM FRP, DIC, Serviceability, Experimental Study.

1142 - Effect of Matrix on Flexural Capacity of Masonry Members Strengthened with Composites

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Abstract: Intervention strategies were performed in many engineering applications. In particular, for brittle materials (e.g masonry) the strengthening strategy must be performed improving also the ductility capacity. However, many of the available models both in the literature and in the building codes are not able to accurately account for the behaviour of strengthening systems on the capacity of strengthened elements. In particular, they provide reliable results for composite based on organic matrix (i.e. resin). For these strengthening systems, matrix contribution can be neglected. For strengthening systems based on inorganic matrix (i.e. cementitious or lime-mortar) the stiffness and strength of the matrix provides non-negligible effects on the ultimate behaviour of strengthened elements.
In this paper, a generalized approach is proposed to assess the out of plane flexural behaviour of masonry sections strengthened with composites. The flexural behaviour has been strictly related to the mechanical parameters of both masonry and strengthening system. In particular, the impact of matrix compressive strength has been evaluated in terms of ductility capacity of the strengthened masonry elements.
Finally, the process of adimensionalization, allows to extend the results to virtually any case, providing a useful tool not only for verification but also for the design of interventions.

Keywords: numerical evaluation, FRP, FRCM, compressed matrix, out-of-plane behaviour.

1143 - Retrofit of Masonry Walls with Composites to Reduce Vulnerability to Tsunami Loads

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Abstract: In the last years, tsunami events caused great damages in terms of buildings collapse and casualties. In general, a masonry wall, subjected to tsunami loads, could reach failure for out of plane mechanism (bending and overturning) or in plane collapse (sliding, cracking by diagonal tension and crushing by diagonal compression), depending on the direction of the flow, if it is parallel or perpendicular to the masonry wall plane. In Scientific literature, several solutions can be found on the improvement of structural response using Textile Reinforced Mortars (TRM). The advantages of designing retrofit interventions with innovative strengthening systems have been remarked continuously.
This paper focuses on the behaviour of masonry walls and the impact of the strengthening solutions using innovative TRM systems. There is a significant improvement of the strength even applying a single layer of material to the sides of the walls. The typology of masonry has been found to significantly alter the wall performance. The same strengthening system is expected to be more efficient in the case of weaker masonry walls, compared to stronger masonry; this depends also on the failure mode of Un-Reinforced Masonry, URM. In particular conditions, high composite mechanical ratios could be useless.
Another aim of the paper is to provide fast assessment tools for the effects of tsunami actions on masonry structures, assuming as main parameter the inundation depth, and to provide a comparably fast tool to design retrofit interventions with innovative strengthening systems, also by means of design charts. In addition, a critical discussion is proposed on the influence of the main mechanical and geometrical parameters of masonry wall and of the composite system on the structural response of the masonry wall cross section.

Keywords: large scale analysis, masonry, strengthening design, tsunami.

1204 - Enhancing Fire Resistance Rating of Reinforced Concrete Members Strengthened with Externally Applied FRP Composites

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Abstract: Fiber reinforced polymer (FRP) systems have been widely used for strengthening of concrete members to accommodate various load increase needs. While FRP strengthening systems are designed to provide the required strength increase, the strengthened members also need to accommodate the new higher loads under fire conditions and meet the code specified fire resistance rating requirements. The fire resistance rating of FRP strengthened members can be enhanced using external fire protection systems, such as fiber boards, fiber blankets and spray-applied fire resistive materials. Current codes and standards such as ACI 216.1, PCI and Eurocode 2 do not provide any guidelines on how to calculate the fire resistance rating of concrete members with supplemental fire protection systems. This paper presents a rational design approach for evaluating the fire resistance rating of RC members strengthened with FRP and protected with cementitious spray applied fire protection systems. The proposed rational fire design approach mainly involves establishing thermal material properties of fire protection system, establishing fire performance of fire protection system through full-scale fire test, performing thermal analysis using finite element approach, performing sectional analysis at elevated temperatures and validating the design approach with data obtained from full-scale fire tests.

Keywords: FRP, reinforced concrete, strengthening, fire resistance rating, spray applied fire-proofing, fire protection system.

1240 - Strengthening in Shear of RC T-beams with CFRP fabrics: Multilayer versus Monolayer

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Abstract: In recent years, manufacturers have developed new heavyweight CFRP sheets as an alternative to multilayer of lightweight CFRP to strengthen important RC structure components. However, there are still design and practical issues that need to be investigated, such as (i) the maximum number of CFRP plies that can be installed without exhibiting slippage or debonding, particularly when bonded on vertical surfaces; (ii) the effectiveness of shear strengthening with multilayer CFRP fabrics compared to a monolayer of equivalent total weight. The present study aims to evaluate and compare experimentally the behavior of reinforced concrete (RC) T-beams strengthened in shear with multilayer lightweight CFRP fabrics to that of a heavyweight CFRP monolayer of equivalent total weight. To this end, nine laboratory tests were performed on eight specimens strengthened with CFRP sheets in U-wrap schemes around the web and bonded continuously along the shear span, and one control specimen with no strengthening. The results are presented in terms of failure modes, gain in capacity due to CFRP, deflection, and strain responses experienced by the externally bonded CFRPs. Finally, the experimental results obtained are compared to the predictions of the current design codes and guidelines.

Keywords: RC T-beams, shear strengthening, CFRP fabrics, multilayer, monolayer.

1243 - Tests of Authentic Low-Performance Concrete Specimens Strengthened with CFRP Sheets

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Abstract: Many existing old buildings constructed in Israel several decades ago are still in service and are likely to remain so for a relatively long time. Such buildings were commonly built using poor materials and construction practices. They include exterior walls, as well as interior partitions, which form part of the vertical gravity structural system. These walls are made of un-reinforced low-performance concrete (LPC) characterized by the presence of large aggregates (about 100 mm or more). Furthermore, in many of such old buildings, LPC walls are the sole vertical structural elements that carry gravity loads and support the floor slabs. Apparently, these old structures were neither designed nor constructed to withstand seismic actions. Yet, these walls usually have relatively medium to large dimensions, and hence, they possess considerable stiffness. Together with non-negligible mass, these walls are likely to attract substantial lateral seismic loads during future earthquakes. Strengthening of LPC walls requires knowledge of their mechanical properties, especially their shear resistance, which is the main object of the present study.
Evaluating shear resistance is commonly done by testing beam specimens designed to fail in shear. For this purpose, authentic samples were extracted from existing walls and sawed into beams with spans of 70~100 cm and cross-sectional depth of ~18 cm. Yet, because these walls are un-reinforced, they had to be strengthened which, in the present study, this was carried out with carbon fiber-reinforced polymer (CFRP) sheets in order to prevent flexural failure during standard three-point-bending tests, thereby allowing them to reach their shear capacity. The paper provides the parameters that governed design of these tests, such as the CFRP properties and its anchorage, a/d ratios of the specimens and the low compressive and tensile strengths of the concrete. Tests that have been conducted so far yielded the desired failure in shear, and the analysis of their results are presented in the paper.

Keywords: low-performance concrete, FRP, shear strength, existing structures.

1246 - Prediction of Deflection Progression of RC Beams Strengthened with NSM FRP Composites

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Abstract: Deflection progression of Reinforced Concrete (RC) beams under cyclic loads gives a reliable indication of the accumulation of fatigue damages. Excessive increase in deflection of RC beams raises a red flag for an immediate need for rehabilitation. This paper presents an analytical model for predicting the deflection progression of RC beams strengthened with Near Surface Mounted (NSM) Fiber Reinforced Polymer (FRP) reinforcement. The analytical model was validated and compared to experimental and numerical analyses. Three-dimensional strengthened RC beam was modeled using ANSYS software with similar dimensions and material properties of specimens that were experimentally tested. Numerical simulations were performed for the RC beam under tension-tension constant amplitude cyclic loads. The analytical model predicted the increase in deflection because of the cyclic creep of concrete during the fatigue life of RC beams. Satisfactory correlation and consistency were noticed between the numerical and analytical predictions with a mean error of deflection less than 9.5%.

Keywords: Bridges; RC beams; Fatigue; Finite element analysis; NSM.

1257 - Damage Identification in NSM FRP Strengthened RC Beams Using Linear Mixed Effects Models

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Abstract: The use of fibre reinforced polymers (FRP) in civil construction applications with near-surface mounted (NSM) method has gained considerable popularity worldwide and can produce confident strengthening and repairing systems for existing concrete structures.
The bond among FRP composites-concrete is very important to the accomplishment of the NSM FRP strengthening system. Different failure types (concrete crushing, FRP rupture, debonding) have been recorded in the literature about the bond among NSM FRP-adhesive-concrete.
Structural Health Monitoring (SHM) traditionally refers to the process of implementing monitoring systems to measure structural responses in real-time and to identify anomalies and/or damage at early stages. Until now, little research effort has been devoted to the identification of damage at its earliest stages for this kind of reinforcement technique. In this work we will use linear mixed effects models as a statistical tool to assess the structural integrity of our subject structures from electromechanical impedances captured from PZT sensors installed on NSM FRP RC beams to be inspected. This type of models is an extension of linear regressions models that describe the relationship between a responsive variable and independent variables. They contain both fixed effects and random effects. Fixed-effects terms are usually the regression part, while the random effects are generally associated with individual experimental units drawn from a population.

Keywords: Mixed Effects Models, NSM FRP, Structural Health Monitoring, Impedance.

1284 - Numerical Investigation on Size and Shape Effects on Hybrid FRP Strengthened Non-Circular RC Columns under Axial Compression

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Abstract: The objective of the study is to investigate the size and shape effect on the efficiency of hybrid Fibre-reinforced polymer (FRP) strengthening of non-circular reinforced concrete (RC) columns under axial compression. FRP strengthening through external bonding (EB) is effective for the confinement of RC columns under axial compression. However, the EB technique is less effective for sections with an aspect ratio (breadth/ depth) of more than two. Thus, ACI 440.2R does not consider the beneficial effect of FRP external confinement of columns with an aspect ratio greater than 2.0. Also, the effectiveness of the FRP confinement through EB reduces with the increase in the column size. Though near-surface mounting (NSM) of FRP laminates is less effective under pure axial compression, it can be helpful to meet the increase in strength demands of columns of large size and different shapes. Thus, the hybrid FRP strengthening technique used in this study combines the advantages of EB and NSM techniques. This study focuses on the numerical investigation using a nonlinear finite element analysis software, ABAQUS. Twenty RC non-circular column specimens of 150 mm depth and different size ratios (1.0, 1.5 & 2.0) and aspect ratios (b/d = 1.0, 2.0 & 3.0) are modelled using finite element technique. Different specimens such as (i) control RC with no strengthening, (ii) RC strengthened with EB, (iii) RC with NSM and (iv) RC with hybrid FRP strengthening technique are modelled and studied. The results of the FE analysis are validated using experimental results available in the literature. The validated FE models were used for a detailed parametric investigation to understand the effect of the hybrid combination of NSM ratio (0.4% to 1.6%) for a constant EB ratio. FE results show that hybrid FRP strengthening is effective in strength and ductility improvement of columns with larger size and aspect ratio than other techniques.

Keywords: RC column, Size effect, Shape effect, Aspect ratio, EB, NSM, Hybrid FRP strengthening and axial compression.

1292 - Quick Reparation of Infills in RC Frames after Seismic Damages – Experimental Tests on Shaking Table

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Abstract: Within SERA Horizon 2020 INMASPOL project, the paper reports the first results from seismic tests on shake table for a real scale reinforced concrete (RC) frame building with modified orthoblock brick wall infills. The building received innovative protection using polyurethane resin (PU) flexible joints (PUFJ) at the frame-infill interface together with the use of PUs for bonding glass fiber grids to the weak masonry substrate, to form Fiber Reinforced PU (FRPU) as emergency repair. The tests validated the advanced in-plane and out-of-plane infill performance under suitably designed seismic excitations. The PUFJ protection enabled the quick repair of the infill even after very high inter-storey drifts of the structure. In addition, the applied glass FRPU repair system efficiently protected the damaged orthoblock infills against collapse under out-of-plane excitation while they restored large part of their in-plane stiffness as well. In this paper, the performances of the FRPU applications under simulated seismic excitations are reported.

Keywords: Seismic areas, quick reparations, RC frames, masonry, infills, fibre reinforced polyurethane, shaking table tests.

1332 - Crack Development in Normal Section of RC Elements Strengthened with Pre-Stressed FRP Under External Load Action in Bending

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Abstract: Nowadays, fibre reinforced polymer (FRP) reinforcements are considered as appropriate strengthening solution for reinforced concrete (RC) structures worldwide. FRP materials gained its popularity due to reduced labour cost, corrosion resistance, good compliance to aesthetical and design requirements. Generally, strengthening is required for structures with deflections and crack widths exceeding design limits, therefore FRP reinforcement needs pre-stressing. Unfortunately, there is a lack of such research and the behaviour of such structures is described on the basis of research data where RC elements worked with FRP reinforcement altogether from the start of loading. The behaviour of the structure will be different in practice. For the above reasons, a crack computation model was proposed, which allows to predict the development of the crack taking into account the influence of external load action and pre-tension of the FRP reinforcement. The proposed calculation model was validated by experimental data of the beams strengthened with different FRP reinforcements, taking into account effects of FRP pre-stressing and initial stress-strain state of concrete elements.

Keywords: fibre reinforced polymer, strengthening, crack width, reinforced concrete.

1344 - Experimental Study on Flexural Behaviour of ECC-Concrete Composite Beams Strengthened with Carbon Fiber Sheet

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Abstract: In order to study the flexural behaviour of steel reinforced engineered cementitious composite (ECC)-concrete composite beams strengthened by carbon fiber sheet (CFS). Totally 12 ECC-concrete composite beam specimens with three types of ECC height replacement ratios strengthened by different layers of sheet and anchorage method (with and without CFS hoops) were made and their static flexural performance tests were conducted. The effect of layers of CFS, ECC height replacement ratio and anchorage method on the bearing capacity, deflection, crack and failure mode of strengthened ECC-concrete composite beams were investigated. The test results show that compared with the unstrengthen beams, the crack width of strengthened ECC-concrete composite beam and the bearing capacity increased by 63 % with the increase in the number of reinforced layers. The ultimate bearing capacity of the beams strengthened with CFS hoops increased by 8.6 % when compared with that of counterpart without CFS hoops.

Keywords: carbon fiber sheet (CFS), engineered cementitious composite (ECC), concrete, composite beam, flexural behaviour

1352 - Prestressing Effects of Jacking-Cambered Wood Beams Reinforced with FRP Strips

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Abstract: When a wood beam is cambered by jacking and then bonded with a laminate of fiber reinforced polymer (FRP), the established prestress is low due to the limitation of interfacial bonding capacity. In this paper, self-locking anchorage is added to the strip end of FRP to prevent the debonding failure, which results in cambered beams with end anchored or hybrid anchored FRP. The relations of the FRP tensile stress, effective compressive prestress at the bottom of the beam, and retained camber with the jacking force and the related parameters of the beam and FRP strip are obtained by detailed derivation. The results show that when the FRP tensile stress is critical at the limit state, the lower stress in a cambered beam with end anchored FRP is advantageous to bear greater external load without fracture of FRP. If the ultimate behavior of a cambered beam reinforced with FRP is dominated by conditions of the original beam, hybrid anchorage can achieve larger camber and compressive prestress at the bottom of the beam, which is conducive to counteracting the deflection in service and tensile stress produced by the load.

Keywords: FRP strip; prestress; camber; reinforcement; strengthening; beam; anchorage.

1422 - Torsional Behavior of Reinforced Concrete Members Wrapped with CFRP Sheets

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Abstract: This paper presents the torsional behavior of reinforced concrete (RC) members fully wrapped with carbon fiber-reinforced polymer (CFRP) sheets. A total of twelve rectangular RC specimens of identical cross sections were tested under pure torsion (beams) or combined axial compression and torsion (columns). In the case of column specimens, an axial force simulating the service loads was applied before CFRP strengthening and maintained constant during the static test under torsion. The magnitude of axial force was 25% of the nominal compressive strength. Therefore, test variables included the presence of axial force (beam or column), stirrup spacing (75 or 150 mm), hook angle (90 or 135 degree) of the closed stirrups, and presence of CFRP sheets. Test results showed that the externally bonded CFRP sheets significantly increased the cracking, yielding, and maximum torsional moment capacities of RC beams and columns. The full wrap configuration enhanced the maximum torsional moment capacity by up to 190% and 116% for RC beams and columns, respectively. Also, the use of 135-degree hook for closed-stirrups was more effective than 90-degree hook for both unwrapped and CFRP-wrapped members. Finally, the effective CFRP strain equation by fib14 correlated better with RC beams than columns.

Keywords: Torsion, fiber-reinforced polymers, strengthening, reinforced concrete members, full wrapping.

1423 - Strength of RC Beams with an FRP-Strengthened Web Opening

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Abstract: Web openings often need to be created in existing reinforced concrete (RC) beams for the passage of utility ducts and/or pipes. Such web openings lead to significant decreases in the load-carrying capacities of the beams due to the reduced cross-sectional area and/or severing of some of the existing stirrups. Therefore, an externally bonded fiber-reinforced polymer (FRP) strengthening system is often applied around the web opening to ensure the safety of the weakened beam. A number of existing experimental and numerical studies have provided useful information on the structural behavior of RC beams with an FRP-strengthened web opening. However, it is desirable to develop a simple strength model for RC beams with an FRP-strengthened web opening, if only the strength of such beams is of concern. This paper proposes a strength model for RC beams with an FRP-strengthened web opening for engineering use. Test results are compared with the predicted results using the proposed strength model to verify the accuracy of the model. A good agreement between the predicted and test results is obtained and therefore the proposed strength model is recommended for engineering use.

Keywords: Reinforced concrete (RC) beam, web opening, fiber-reinforced polymer (FRP) strengthening, FRP confinement, strength model.

1452 - Flexural Analysis and Optimized Design Software for Reinforced Concrete Beams Strengthened with NSM or Externally Bonded FRP

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Abstract: The flexural strengthening techniques of reinforced concrete beams using Externally Bonded (EB) FRP sheets or Near Surface Mounted (NSM) FRP bars have been very well established. The technology transfer has taken place into engineering design practice for two decades now through the introduction of design guidelines. However, the lack of design software in the market as well as the limited academic education of present engineers has been an obstacle against the wide spread of this technology as a preferred alternative for repair and strengthening. Recently, a US-based group has responded to this need by developing professional interactive software to analyze and design structural elements strengthened with FRP. One of the very first products that came out of this effort was the development of a detailed analysis and design tool on strengthening of RC beams. This software complies with the provisions of ACI 440.2R-17 and is available interchangeably in SI and US customary unit systems. It is capable of analyzing rectangular, T and inverted L sections strengthened with externally bonded FRP or NSM bars. It allows for one compression layer and three tension layers of steel and provides strength and serviceability calculations. It has a graphics tool for to-scale drawing of sections, and it offers a detailed professional design report. The premium version is equipped with a graphics based optimized design feature that eliminates the need to perform design iterations. Its user-friendly interface is an asset to any design office.

Keywords: Design Tools, Flexural Strengthening, RC Beams, FRP Sheets, NSM Bars.

1458 - Debonding Failure in RC Beams Strengthened in Flexure with Cfrp Strips: Mitigation Using Cfrp U-Jackets

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Abstract: The excellent performance of near-surface mounted (NSM) fiber-reinforced polymer (FRP) method in enhancing the flexural capacity of reinforced concrete (RC) beams has been proved by abundant experimental studies over the last two decades. However, premature debonding of FRP in NSM FRP flexurally-strengthened RC beams was still frequently observed, which significantly limited the utilization of expensive FRP materials. To delay/suppress debonding failures and further improve the beam performances, the use of FRP U-jackets as the anchoring measure for NSM reinforcement in the strengthened beam is an attractive approach. Although there have been a number of relevant experimental studies, tests on the large-scale RC beams are still very limited. Against this background, an experimental study consisting of 4 large-scale RC beams strengthened with NSM CFRP strips was carried out to investigate the effect of CFRP U-jackets on the flexural behavior of such strengthened beams. Test results show that the CFRP U-jackets arranged at the ends of NSM FRP strip can effectively suppress the end concrete cover separation failure and thus enhance the load and deflection capacities of the NSM FRP strengthened beams.

Keywords: Near-surface mounted (NSM), fiber-reinforced polymer (FRP), flexural strengthening, debonding, FRP U-jacket, reinforced concrete (RC) beams.

1480 - Experimental analysis of R.C. beams preloaded, repaired and flexural strengthened with carbon fibre reinforced polymer (CFRP)

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Abstract: Concrete is a material widely applicable in structures all over the world. Therefore, its deterioration and problems caused over time are inevitable. Considering this fact, the structures of concrete recovery is a real need. There are numerous techniques structural recover and repair. The system using carbon fibre reinforced polymer (CFRP) is among them. CFRP is lightweight, presents high tensile strength and is easy to be installed. This research presents an experimental analysis about the monotonic flexural behaviour and ultimate capacity of ten reinforced concrete beams partially damaged and cracked after preloading in flexure. The beams were externally repaired using one or two layers of CFRP fabrics and bonded with epoxy resin over a pre-treated substrate aiming better adhesion. Each beam was loaded and tested by a flexural tensile strength in four points bending test. The ultimate load and maximum deflection were recorded. The aim of this study was to verify the effectiveness of the CFRP as strengthening of the damaged structure of reinforced concrete. It was observed that specimens strengthened with one layer of CFRP increased, in average, 49,70% of the flexural tensile strength while using two layers improved it in 56,66% when compared to the control beams with no additional external reinforcement. When analysing the actual behaviour of the CFRP reinforced beams with the designed, it was observed an average achievement 4,65% less than the expected for the group using one layer and 5,05% less with 2 layers of CFRP. Therefore, the accuracy of the results was satisfactory when compared to previous values obtained. During the structural analysis, it was observed that the shear force caused the failure of the beams. Additionally, it was verified the effectiveness of the CFRP when used as an external strengthening to recover the damaged structures of reinforced concrete studied, submitted to their ultimate flexural tensile load.

Keywords: Structural Strengthening, Reinforced Concrete, Structural Repairs, CFRP, Carbon fibre

1481 - Experimental Study on Mechanical Properties of Bamboo Culms and Joints Reinforced with GFRP Sheets

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Abstract: Bamboo is a kind of a green renewable traditional building material with the advantages of high tensile strength parallel to grain and fast growth, which can meet the development needs of green and ecological fabricated buildings. However, the round bamboos are likely to crack under pressure, especially at the bottom of the column and bolted bamboo joint, because of stress concentration. To solve the above problems, glass fiber reinforced polymer (GFRP) was used to strengthen the natural bolted bamboo joints in this study. Then shear tests and pressure tests were carried out in order to find an effective way to improve the compression resistance capability of the bamboo column and shear behavior of bolted bamboo joint. The bearing capacity and failure modes were observed and studied. Compared with the specimens without reinforcement, the maximum deformation capacity of the GFRP reinforced bamboo column specimens is increased by at least 2.5 times, and the bearing capacity is increased by 5.5% - 11.7%; the maximum deformation capacity of the GFRP reinforced bamboo joint specimens is increased by at least 2.5 times, and the bearing capacity is increased by 3-6 times. Therefore, GFRP is a kind of material which can greatly improve the deformation and bearing capacity of bamboo column or bolted bamboo joint. In addition, GFRP can prevent brittle failure and improve ductility of specimens.Although the bearing capacity of GFRP reinforced bamboo joints has been greatly improved compared with that without reinforcement and the stress has also been greatly enhanced, the maximum load that the bamboo joint can bear is still far lower than that of the bamboo column due to the lack of bearing area. How to make full use of the bearing capacity of bamboo in addition to the node is the key point to be solved in the future, one suggestion is to add fillers to bamboo joints.

Keywords: fiber reinforced polymer, bamboo culm, partially reinforcement, bamboo joint.

1497 - Strengthening of Recycled Concrete Aggregates Two-way RC Slabs by Externally Bonded CFRP

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Abstract: The use of recycled concrete technology has become an international urgent demand owing to the rapid growth of construction industry along with the deteriorating ecological environment situation worldwide. Promotion of use of recycled concrete, can not only effectively reduce construction waste pollution to the natural environment, but also can reduce mining of the natural aggregate, which contributes to the sustainable development. Numerous investigations have been conducted on the use of recycled aggregate in concrete structures for more than a decade, and the relevant laboratory testing and field investigation results have showed that concrete structures built with recycled aggregates had good bearing capacity, deformation ability and earthquake resistant energy dissipation capacity. However, not that much attention has been paid in investigating the behavior of reinforced concrete two-way slabs cast with recycled concrete aggregates. This paper presents the results of a detailed experimental investigation conducted to study the behavior of the reinforced concrete two-way slab cast with recycled aggregates. Eight reinforced concrete two-way slabs with confined columns attached at the center of the slabs were cast using both natural and recycled aggregates. Two slabs each, cast with natural and recycled aggregates, served as control for respective types. Remaining four, two each from natural and recycled aggregates, were strengthened with carbon fiber reinforced polymer (CFRP) strips. Based on the experimental study, it was found that strengthening of two-way slabs containing natural and recycled aggregates was effective and capacities of the slabs increased by 37% and 35% respectively. Punching capacities of the slabs were also predicted by using the expressions available in literature and were compared with the experimentally observed capacities. Predicted values were found to be in close agreement with the experimentally observed values.

Keywords: Recycled aggregate concrete, reinforced concrete, two-way slabs, punching strength, CFRP.

1501 - Interface Response of CFRP Fabrics for Concrete Substrates Enhanced with Toughened Epoxy Adhesive Layers.

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Abstract: Superstructures such as reinforced concrete bridges, often suffer from exposure to extreme corrosive environments. The corrosion of the reinforcement leads to a decrease of their capacity and their structural performance needs to be upgraded with strengthening measures. Lately, the use of Fiber Reinforced Polymers (FRP) in retrofitting schemes has attracted a lot of attention. In this paper the interface response of adhesively bonded Carbon FRP (CFRP) fabrics applied on concrete substrates is investigated. This paper deals with the study of the integration of CFRP fabrics using different adhesive layers as the composite's matrix, first using a conventional adhesive and next using an enhanced toughened adhesive layer. Two different scenarios of substrate integrity were studied: a) healthy concrete and b) substrate with corrosion products. The bond-slip behavior of the interfaces between concrete and the laminated fabrics was investigated with a modified double shear test configuration. The use of the toughened matrix increases the shear stresses up to 61% in failure, nonetheless in significant lower ratio of strains. The corrosion reduces the maximum shear stresses of the interface up to 20% and the corresponding strains up to 23% in failure. For the scenario were the toughened matrix was used, there is a shift in the response from a pseudo-ductile to linear with a tendency to fully elastic. The crack propagation is depicted in distinct stages. The use of toughened adhesive layers with reduced stiffness shifts the mindset of creating high stiffness retrofitting solutions to achieve high mechanical performance and still ensures an efficient strengthening response.

Keywords: CFRPs, toughened adhesives, nanoparticles, interfaces, corrosion.

TESTING

1040 - Diagonal Shear Tests for Glass Fiber Reinforced Gypsum (GFRG) Panels with and without Concrete Filled Cells

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Abstract: This study presents results from a number of glass fiber reinforced gypsum (GFRG) wall specimens that were monotonically tested at an angle of 45° and under increasing vertical load. Several infill configurations are considered to see possible changes in strength, stiffness, and failure modes. Eight samples with 770 mm x 770 mm x 124 mm side dimensions were prepared to be used in the diagonal shear tests. Concrete and steel reinforcement (rebar) elements were added to the system to achieve the required strength, stiffness, and ductility. C25 concrete grade and Ø12 steel deformed rebars with a steel grade of S420 were used in these samples. The samples were forced to collapse under a monotonically increasing load. Overall behavior was observed and behavioral values such as ultimate shear strength and initial wall shear rigidity/stiffness values were determined. Related load-deflection curves are given. According to the data that were gathered from the experiments, unfilled specimens and specimens filled with concrete at the middle or edge cells had load capacities around (70~85) kN, while fully concrete filled specimens achieved capacities up to (260~270) kN. Experimental results show that filling the edge or middle cells with concrete (i.e. sort of partial filling) has no significant effect on shear capacity when compared to unfilled samples. Crack patterns developed especially within the unfilled cell regions. The fully concrete filled panel, on the other hand, had a significant impact (approximately 3~4 times) on the capacity when compared with the unfilled case. The rebars used in the fully filled samples had no significant effect mainly from the occurrence of separation between the concrete core and GFRG panel for this type of loading but it increased initial stiffness. When the whole system is compared, concrete filling and rebar increase the initial stiffness of the sample. Filling the edge or middle cells with concrete (with and without rebar) has increased the initial stiffness between (1.17~1.47) times when compared to unfilled samples. Fully concrete filled panel (with and without rebar) had a significant impact (1.97~3.66 times) on initial stiffness when compared with the unfilled samples.

Keywords: GFRG, Diagonal Shear Test, Shear Strength, Shear Rigidity/Stiffness, Initial Stiffness.

1076 - Carbon reinforced concrete members under concentrated load

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Abstract: Many buildings are already realized with elements made of textile reinforced concrete. This innovative composite material offers numerous advantages, such as low concrete covers and a good corrosion resistance. Many aspects of textile reinforced concrete constructions have mostly been investigated, for example the bending and bond behavior of textile reinforced concrete members. However, there are still largely unknown fields of research such as the load case "concentrated load" in façade panels which are caused, for example, by the suspension of the panels. So far, there is no general design approach for this case and a gap in knowledge was identified. Due to an increasing application of textile reinforced concrete elements, the design of thin panels under concentrated load is of great importance.

This paper presents the results of the experimental investigations on carbon reinforced concrete members under concentrated load. In addition to the test results, first conclusions for carbon reinforced concrete members for such load cases are presented.

Keywords: carbon reinforcement, textile reinforced concrete, concentrated load, façade panel.

1082 - Assessment of Steel-Composite and Concrete-Composite Adhesively Bonded Joints by Acousto-Ultrasonic Technique

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Abstract: In civil engineering, structural adhesive bonding is increasingly used as an assembly method for the reinforcement or rehabilitation of old structures by composite materials. However, the presence of defects within the bonded joint may affect the effectiveness of the assembly, and their detection is still an issue. The purpose of our study is to use the acousto-ultrasonics (AU) approach to detect, identify and assess the severity of all types of defects within adhesively bonded joint.
In this paper, we will present at first our test specimens that are pultruded plates manufactured with unidirectional carbon fiber reinforced polymer and bonded on steel or concrete support with three types of defect (voids, kissing-bonds defects reproduced by a layer of grease at the composite-adhesive interfaces, and weakly polymerized zones implemented by softening the adhesive). We will then introduce the AU equipment (sensors, coupling, emission and reception systems) and its final configurations that were developed through extensive preliminary investigations and adapted for both types of assembly. After that, we will provide information concerning the robustness of the methodology, investigating the repeatability and reproducibility of the measurements using a statistical correlation approach as assessment strategy. Finally, we will discuss the results, which proved good detection of each defect using a Principal Component Analysis. These results are offering good perspectives for the use of AU technique for the control of adhesively bonded joints. Additional investigations are currently under progress in order to propose identification procedures for each type of defect and to assess the severity of each defect regarding the bonded joint mechanical properties.

Keywords: Acousto-ultrasound, Non Destructive Technique (NDT), Adhesively bonded steel-composite assembly, Adhesively bonded concrete-composite assembly, PCA

1148 - GFRP Beam-to-Column Connections Using Stainless Steel Cleats

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Abstract: Pultruded glass fibre reinforced polymer (GFRP) profiles are increasingly finding their way in civil engineering structural applications. The design of GFRP connections between profiles is of great relevance, as they influence the members' deflections and often govern design at ultimate limit states, being prone to brittle failure modes. The first part of this paper presents an experimental campaign on the monotonic and cyclic behaviour of beam-to-column connections using stainless steel cleats. Stainless steel was chosen for the cleats owing to its corrosion resistance (compatible with GFRP) and its ductility. In order to maximize strength and/or ductility, several cleat configurations were tested, varying their wall thickness, length, number of bolts and back flange reinforcement. The results show that this connection system, particularly with back flange reinforcement, presents significant ductility and energy dissipation capacity. In the second part of the paper, a design-oriented analytical study is presented, based on the component method and (common) steel structural design procedures, to estimate the stiffness and strength of the connections – the method was able to predicted with reasonable accuracy the behaviour of the connections.

Keywords: Bolted FRP connections, Monotonic loading, Cyclic loading, Experimental tests, Design.

1176 - "Feasibility Study on the Recycling of FRP Materials from Wind Turbine Blades in Concrete".

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Abstract: This paper presents the results of an experimental investigation to study recycling-methods of Fiber-Reinforced Polymers (FRP), extracted from Wind-Turbines Blades into concrete. Chemical composition (non-organic), mineralogical analysis, organic content, pozzolanic activity were examined. The effects of adding waste wind-turbine blade FRP-material (WTB-FRP) into concrete as a partial replacement of cement and fiber reinforcement were studied under the uniaxial compression and 3-point bending load. According to the test results, the high wooden content caused significant increase in the setting time of cement paste (up to 4 days for 40% of cement replaced) and significant drop in compressive and flexural strength if added as powder due to the retardant properties of wood powder and its high water absorption. The concrete mixture tests for the fibers showed slight decrease in compressive strength (up to 4% for 1,25% of fibers by weight) and increase in flexural strength up to 15%. No deterioration of E-glass by high alkalinity of hydrated cement was observed due to the protective layer of polymer formed around the fibers.

Keywords: Concrete, Glass Fiber Reinforced Polymer (GFRP), Recycled Materials, Wind Turbine Blade.

1182 - Structural Performance of All-Composite GFRP Bridge Girder

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Abstract: A very good application of FRP composites has been proved in case of hundreds of pedestrian bridges. However, there exists only very few of all-composite bridges that are suited for the heavy traffic load classes. The innovative idea of an all-composite girder-deck structural system for small bridges suited for the heavy traffic load classes has been proposed and experimentally tested under static and dynamic load. The all-composite bridge girder is combined with a U-shaped open box with slightly inclined webs and two top flanges and a sandwich slab bonded to the top flanges with epoxy adhesive. The composite action of both elements under service load was assumed in the design of the bridge superstructure. The top and bottom flanges of the box were made of solid GFRP composites whereas the webs were made in form of the sandwich panels with PVC foam layer in-between two GFRP laminates. The sandwich bridge deck slab consisted of two GFRP laminates and PUR foam core stiffened with the internal vertical GFRP ribs. To increase the torsional stiffness of the girder and to prevent buckling of webs, internal diaphragms were placed and bonded along the length of the girder. The most important issues in structural behavior of all-composite bridges are: girder stiffness, ultimate strength, failure mode, strength of its longitudinal adhesive joints and global safety factor. These performance characteristics of the new all-composite bridge girder have been evaluated on the basis of static load tests carried out on the full-scale model. After comprehensive laboratory testing, which had revealed expected structural performance, the girder was used in the first Polish all-composite bridge.

Keywords: all-composite bridge girder, structural testing, stiffness, strength, safety factor.

1313 - Mechanical Characterization of GFRP Through Experimental Dynamic Testing

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Abstract: The use of pultruded glass-fiber reinforced polymer (GFRP) has increased in recent years, with important applications for footbridges, bridge decks, cooling towers, among other. The mechanical characterization of GFRP in terms of elastic properties is often carried out by means of destructive static tests specified in international standards, but it may be a quite tedious activity given the number of properties to be determined. An alternative approach consists in the use of non-destructive techniques based on dynamic testing, also known as experimental modal analysis (EMA). This work aims to identify the dynamic properties of thin-walled GFRP members regarding their natural frequencies, mode shapes and damping ratios. These experimental dynamic characteristics obtained for a C-channel beam are, then, used to determine specific material elastic properties back-calculated using numerical optimization process. It is shown that the properties determined through dynamic testing are in relatively good agreement with those obtained from classical destructive tests. This non-destructive technique is an alternative approach for the mechanical characterization of GFRP members, especially important for low cost in situ quality control.

Keywords: Glass-fiber reinforced polymer, dynamic testing, experimental modal analysis, mechanical characterization.

1330 - European Assessment for GFRP-Sandwich Connectors

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Abstract: For more than 25 years sandwich connectors made from GFRP are known in different markets. In different parts of the world, national committees or authorities have defined different testing programs to assess the performance of such elements. Now in Europe an internationally counselled assessment document (EAD) is available and the first producers have submitted their evaluation reports. In this paper, the background, as well as some results of this EAD, are presented and discussed.
The focus of this paper is on the evaluation of the thermal effects on the load-bearing capacity of sandwich connectors. In particular, the temperature effect causes cyclic shear and bending stress in the connector due to the temperature difference between the facing layer and the load-bearing layer. The effects of the cyclic temperature-induced stress are investigated by functional tests with a subsequent test of the residual load-bearing capacity.
In the context of this article experimental investigations for the evaluation of the temperature-induced cyclic shear and bending stress on the load-carrying capacity of sandwich connectors made of glass fibre reinforced polymer are presented and subsequently evaluated.

Keywords: EAD, ETA, Point Anchor, Sandwich Connector, Certification, Approval, Shear Test.

1337 - Comparison between Direct Shear and Flexural Tests on RC Elements Strengthened with SRG Composites Subjected to Cyclic Loading

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Abstract: Steel reinforced grout (SRG) retrofitting systems represent a suitable technique to increase the performances of reinforced concrete (RC) structures, in particular for structural elements subjected to flexure. They can be applied even to wet surfaces and they feature a better fire resistance with respect to Fiber-Reinforced Polymer (FRP) composites. Nevertheless, the failure mode of strengthened elements can be similar to that of FRPs, i.e. debonding of the externally bonded reinforcement, especially if several layers of composite reinforcement are applied to the RC element. Different studies can be found addressing the problem of bond between SRG and RC or masonry substrates, but only few of them analyzed the bond performance when multiple layers are considered. To this purpose, the present paper presents the results of an experimental campaign focused on this specific key-aspect of the bond behavior, i.e. when multiple SRG layers are considered. Single-lap shear tests were carried out on concrete prisms strengthened by a single or multiple SRG layers, addressing the differences in terms of bond behavior and failure modes. In addition, monotonic and cyclic loading were considered in order to verify the possible bond degradation when applying high amplitude cycles; results of the cyclic loading tests were compared with those from monotonic tests on single or multiple SRG layers with the same amount of reinforcement. Flexural tests were carried out on full-scale RC beams strengthened with multiple plies of SRG reinforcement, without mechanical anchorages. Beams were subjected to either monotonic or cyclic loading. Tests were carried out under displacement control in order to properly characterize the non-linear behavior, evaluating the effect of composite reinforcement in terms of failure mode and ductility. The comparison between both small (single-lap) and full-scale (beams) tests allows to investigate the applicability of the bond relationship developed at small scale to structural elements and to evaluate the possible limits of small-scale testing.

Keywords: SRG, RC beam, flexural test, bond test, cyclic.

1478 - Mechanical Characterization of a Basalt Fabric for TRM Composites: Role of the Test Variables

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Abstract: Textile reinforced mortar (TRM) materials are currently receiving great attention for the strengthening of reinforced concrete and masonry structural elements. Mortars with different strength classes have been coupled with different kind of synthetic fabrics, such as carbon, glass, steel, PBO. Recently natural fibres and, in particular, basalt fibres are receiving increasing interest since they proved to be a promising alternative to the most common synthetic fabrics, thanks to the reduced production costs and the consequent benefits in terms of environmental impact.

This paper presents an experimental investigation comprising forty-one monotonic tensile tests on textile strips made with a primed basalt fibre bidirectional grid. The tests were performed considering the influence of different setup variables, such as the clamping system, the size of the specimens, the measurement device and the testing elongation rate. Part of the tests was carried out by using a video-extensometer for the measurement of the strains, taking advantage from the digital image correlation (DIC) technique. The goal of the work was to find the most suitable configuration for the mechanical characterization of basalt grids, in order to fully exploit the tensile strength. The results showed to be influenced by the different test setup parameters considered. In particular, the outcomes were affected by the slippage of the grid at the gripping zone and by the testing rate.
Keywords: TRM composites, basalt textile, experimental investigation, tensile tests, digital image correlation (DIC).

MINI SYMPOSIUM - ADVANCES AND CHALLENGES IN SEISMIC STRENGTHENING OF RC STRUCTURES WITH FIBRE-REINFORCED COMPOSITE MATERIALS (FRP, FRCM/TRM, FRCC)

1031 - Integrated Structural and Energy Retrofitting of Masonry Walls: The Effect of In-plane Damage on the Out-of-plane Response

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Abstract: In the present study, a total of 12 experiments were carried out in order to evaluate the effect of prior in-plane damage on the out-of-plane response of structurally and thermally retrofitted masonry wallettes, simulating in a that way the behavior of upgraded masonry infills in reinforced concrete or steel frame structures under seismic loading. The specimens were retrofitted with textile-reinforced mortar (TRM), which in some cases was combined with expanded polystyrene as thermal insulation material. Testing comprised in-plane diagonal compression and out-of-plane bending on walls with or without prior in-plane damage. Numerical simulations were also performed using fiber modeling, and they were found in good agreement with test results. In-plane loaded walls with TRM only or TRM/insulation retrofitting outperformed significantly their non-retrofitted counterparts. Out-of-plane loaded walls with combined TRM/thermal insulation performed much better or at least as good as their TRM-only retrofitted counterparts, for the case with or without prior in-plane damage, respectively.

Keywords: energy retrofitting, in-plane loading, masonry walls, out-of-plane loading, seismic strengthening, textile reinforced mortar

1043 - Rapid Heating of Textile Reinforced Concrete: Effect of Textile Coating and Hybrid Textile Layups

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Abstract: The behavior of Textile Reinforced Concrete (TRC) under increased temperatures has been poorly investigated so far and has been a topic of increasing interest in the past decade. The lack of knowledge is even greater when it comes to the behavior of hybrid reinforcement layups, in which different fiber textiles are combined, and the effect of their coating. This paper focuses on the residual tensile behavior of TRC exposed to high temperatures with high heating rates (that correspond to a fire scenario). The investigated parameters are the fiber material (carbon fibers or glass plus carbon fibers) and the textile finishing (coated or uncoated). The specimens (thin tension coupons) were exposed to fire from both sides. Two fire tests were conducted following a standard fire curve (ISO 834) for 7 and 19 minutes and the reached temperatures at the coupons were approximately 200 °C and 300 °C, respectively, uniform through the coupons' thickness. The tensile test results that were conducted on the fire exposed coupons, indicated that the temperature effect on the hybrid layup TRCs is relatively small since the tensile strength and the post-cracking stiffness of the material are mainly controlled by the stronger and stiffer carbon fibers, which are unaffected by these temperatures. Additionally, for temperatures of this level, the effect of the coating seems to be limited, since the residual strength of the specimens with coated textiles was almost unaffected. The post cracking stiffness was either unaffected or even increased, depending on the textile finishing.

Keywords: High Temperature, Hybrid Layups, Fire, Textile Reinforced Concrete, Textile Coating.

1068 - Experimental Investigation on Full Scale Cast in Place R.C. Floor Strengthened with FRCC Strengthening Technique

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Abstract: The cast in place floors of existing buildings realized in Italy in the '60-'70 years are commonly made by longitudinal beams and hollow clay bricks with a top deck without internal reinforcement. Thus, they are unable to properly guarantee the load distribution function over structural members which is strongly required in case of seismic actions. Furthermore, the deck thickness of such horizontal structures is commonly less than the minimum value given by current codes (≥ 40 mm) in order to assume the floor as rigid in plan.
The effectiveness of an innovative system, based on the use of Fibre-Reinforced Cementitious Composite (FRCC), is investigated in the paper as a strengthening technique of these existing floors. Three point bending tests on two full scale cast in place reinforced concrete (r.c.) floors have been carried out: one specimen was tested in the "as built" configuration; one specimen was strengthened with a new FRCC deck, about 2 cm thickness made by fibre-reinforced, shrinkage-compensated, high-strength, high-ductility, highly-fluid cementitious mortar.
The main aspects related to the application procedure of the system, the experimental test setup, as well as the experimental results in terms of crack pattern, strength and deformation of the specimens are herein presented and discussed.

Keywords: Fiber Reinforced Cementitious Composite, full scale cast in place r.c. floor, three point bending test, innovative repair system.

1080 - Rc Columns Upgrade: Opportunities Given by FRP and Potential of FRCC Systems

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Abstract: Fiber Reinforced Polymer (FRP) composites have been widely used in past decades for the seismic upgrading of sub-standard reinforced concrete (RC) members and their effectiveness as a suitable strengthening technique for such kind of structural components has largely been proved. However, some concerns still arise with the effectiveness of such composite materials at high temperature, such as in the case of fire exposure. Furthermore, the use of FRPs requires a minimum quality for the concrete substrate to avoid undesirable premature failure mechanisms. Usually, the replacement of the poor quality or damaged concrete cover of existing members with a new one is needed before the strengthening intervention. Current research is now moving towards the adoption of inorganic composite materials, such as Fiber Reinforced Cementitious Composite (FRCC), for repairing existing RC buildings and infrastructures as a replacement of the original concrete cover, due to its good durability properties and resistance to high temperature. The present study discusses the possibility of adopting such FRCC jacketing also for the seismic upgrading of existing shear critical RC columns. The experimental performance of RC columns strengthened with FRCC jacketing subjected to cyclic lateral loading and different axial load ratios is analyzed herein, and the experimental performance of FRCC and FRP jacketed columns is compared to point out the effectiveness of both retrofit solutions.

Keywords: FRP jacketing, FRCC jacketing, shear strengthening, seismic retrofit, durability.

1174 - Seismic Response Analysis Model for Full-Scale 10-Story RC Building of Shaking Table Tests (FY2015)

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Abstract: The world's 3D full-scale earthquake shaking table test facility, also known as E-Defense, was built by the National Research Institute for Earth Science and Disaster Resilience. The facility confirms the failure mechanisms of full-scale structures during earthquakes and verifies the effects of seismic retrofitting. In December 2015, shaking table tests of ten-story reinforced concrete buildings, of which structural system was the moment-resisting frame on a longer direction and frame with a shear wall on a shorter direction using the E-Defense, were conducted to gain building engineering knowledge about the continued use of buildings after a major earthquake and confirm the seismic performance of buildings designed on the basis AIJ recommendations as well as examine its performance given by the newest Japanese design. In this study, we propose and investigated a numerical analysis model—a lumped mass multiple-degree-of-freedom system - to estimate the seismic resistance structural system used in the 2015 shaking table tests. The hysteretic models for story behavior are determined using the results of nonlinear static pushover analysis.

Keywords: E-Defense, MDOF model, Moment-resisting frame, Frame with shear wall

1281 - Preliminary in-Plain Shear Test of Damaged Infill Strengthened by Frpu

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Abstract: This paper presents results of in-plain shear tests carried out in ZAG laboratory in Ljubljana (Slovenia) on a RC frame with masonry infill made of clay blocks (KEBE OrthoBlock). The frame fixed at the bottom and loaded vertically at columns' tops was excited by horizontal cyclic loads at the top beam level. These loads forced various and gradually increasing drift levels (positive and negative) of the frame, with 3 repetitions at each level. Acquired forces and measured displacements allowed drawing hysteresis loops for determination of dissipation energy. Additionally, Digital Image Correlation (DIC) system was used for visualization of the behavior of the tested specimens.

Three types of specimen were tested. The first one, the reference specimen in form of plain RC frame was forced up to 4.3 % of the frame horizontal drift when significant crushing at the bottom of both RC columns occurred. The second one, the reference specimen with constructed masonry infill without any strengthening was forced up to 1.6 % of the frame horizontal drift when crushing at the corners and complete detachment at the frame-infill interface occurred. The infill would be destroyed even with small out-of-plane forces. In the third one step the damaged infill was strengthened on both sides using glass mesh bonded to the infill and the RC frame using flexible adhesive made of polyurethane matrix. This Glass Fiber Reinforced PolyUrethane (GFRPU) allowed withstanding additional cyclic loads, generating the maximum frame drift of the value 3.6 %, without serious damages disqualifying the structure from further exploitation. The tested GFRPU strengthening system was very effective and resistant to out-of-plane forces (damaging infills in seismic areas).

Keywords: Masonry blocks, damaged infill, FRPU, external composite strengthening, in-plain shear.

1288 - Design Procedure for the Frcc Strengthening of Beam-Column Joints

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Abstract: Existing reinforced concrete buildings were mainly designed with old code provisions. This resulted in lack of proper seismic details and, in turn, the occurrence of premature brittle failures as frequently observed in the aftermath of recent seismic events. The shear failure of the joint panel is one of the main reason limiting the seismic performance of existing structural systems. Several retrofit solutions were proposed in the recent years to improve the joint panel shear strengthening and, nowadays, composite materials are frequently used in the common design practice. The widespread use of fibre-reinforced cement composites (FRCC) and high-performance fibre-reinforced cementitious composites (HPFRCC) opened new frontiers in the design of the shear capacity of RC members. The high tensile strength, toughness, and tolerance for damage make these materials attractive for the use in earthquake-resistant structures, with emphasis on RC members with shear-dominated response. Although several experimental tests demonstrated the effectives of these materials in the seismic retrofit of existing beam-column joint a proper design formulation is still lacking.
This research paper presents a novel procedure for the design of the exterior FRCC jacketing of poorly detailed on beam-column joints. A mechanical model based on the principal tensile stress approach is proposed. The model is later validated against a comprehensive database of experimental tests at global and local level. The proposed procedure allows the designers to calculate the thickness of the FRCC jacketing to avoid the joint panel shear failure and promoting a more ductile failure mode.

Keywords: FRC, UHPFRC, fibre reinforced concrete, seismic retrofit, beam-column joints.

1403 - Development of GFRP Guyed Communication Towers

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Abstract: The demand for a lightweight, reliable, and cost-effective construction material with free maintenance and great resistance to corrosion to replace steel communication towers has become more obvious in recent years. The paper explores the use of glass fibre-reinforced polymers (GFRP), as unconventional materials for the fabrication of lightweight communication guyed towers. The tower examined in this investigation had a uniform constant cross section of three identical cells bonded together to form an equilateral triangle with sides of 500 mm. The communication tower was analyzed using the finite element program ANSYS and was designed to satisfy both the ultimate limit state and the serviceability limit state requirements of the structural standards for antenna towers and antenna supporting structures, EIA/TIA Standard. The experimental work involved the testing of 9 m tower segment under static and dynamic loads and an extensive material testing to define the tower's material properties. This paper presents results from this research project.

Keywords: GFRP, Communication Tower, Guyed Structure, FEM, ANSYS.

1484 - Seismic Performance of Large Rupture Strain (LRS) FRP-Wrapped Circular RC Columns

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Abstract: This paper presents an experimental study on seismic retrofit of circular reinforced concrete (RC) columns with FRP composites. Three RC columns strengthened with Polythylene Naphthalate (i.e., PEN) FRP composite, which has a much larger rupture strain than conventional FRPs, were tested under combined axial loading and cyclic lateral loading. Three conventional CFRP-confined RC columns and one un-strengthened control column were also tested for comparison. The control column was found to fail due to the buckling of the longitudinal steel reinforcement and be of shortage of ductility, while the major role of FRP confinement in cases of slender circular RC columns is to prevent the spalling of concrete cover and the buckling of longitudinal reinforcement. Use of different FRP jackets and FRP stiffness had a marginal effect on the overall load-deformation responses particularly under a lower axial load ratio. Numerical simulations based on OpenSees, into which a cyclic stress-strain model for longitudinal reinforcement previously developed by the authors was implemented, were conducted to facilitate an in-depth understanding of the test results and the corresponding strengthening mechanisms. The cyclic stress-strain model takes into account the buckling effect of steel reinforcement and the lateral confinement effect of FRP jackets. Further parametric studies revealed that under a high axial load ratio (e.g., 0.4), the consideration of buckling of longitudinal reinforcement is of more significance.

Keywords: Large rupture strain (LRS), FRP, buckling, seismic performance

MINI SYMPOSIUM - ADVANCES IN THE INVESTIGATION OF THE BOND MECHANISM OF FRP, FRCM, TRM, AND SRG COMPOSITES

1005 - Fatigue Bond Characteristics of NSM CFRP in Concrete due to Adhesive and Surface Treatment

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Abstract: The interfacial bond characteristics and failure mechanism of near-surface mounted (NSM) fiber reinforced polymer (FRP) composites play an important role in the behavior of NSM strengthened concrete members. This bond characteristics under fatigue loading is less understood comparing to their static performance. In this study, a series of direct pull-out tests on NSM carbon FRP (CFRP)-concrete block specimens were performed under fatigue loading conditions with a sinusoidal waveform at a frequency of 2 Hz. Prior to any fatigue loading, monotonic test was also conducted to respective reference specimens to establish the corresponding static capacity (i.e., ultimate pull-out force). Degradation of the local bond strength is presented in this paper for both CFRP rods and strips under the fatigue load ranging from 10% to 60% of the corresponding static load-carrying capacity. The effect of cross-sectional shape, surface treatment and adhesive type on the fatigue bond characteristics of the NSM CFRP in concrete is also discussed in this paper.

Keywords: Fatigue, Bond performance, Near-surface mounted (NSM), carbon fiber reinforced polymer (CFRP).

1013 - Characterization of Debonding Strain in Lightweight Concrete T-Beams Strengthened in Flexure Using Different Levels of CFRP

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Abstract: The premature debonding of Fiber Reinforced Polymer (FRP) sheets has been well studied and documented for normal weight concrete. This type of failure mode can be averted by keeping the maximum FRP strain below the debonding strain in the FRP as specified by ACI 440.2R-17. However, the debonding strain in light-weight concrete has not been addressed or evaluated yet. Accordingly, this present paper investigates the characteristics of the debonding strain in light-weight concrete using full-scale reinforced concrete T beams strengthened with different levels of carbon fiber reinforced polymer (CFRP). These beams were prepared and strengthened in two series. The first series included three T beams (T1LW, T2LW and T3LW) that were cast with lightweight (LW) concrete. Beam T1LW was tested as a control, beam T2LW was strengthened with 2 layers of CFRP, and beam T3LW was retrofitted with four layers of CFRP. Series two consisted of three other T beams (T1NW, T2NW and T3NW) that were strengthened the same way as series one, but with normal weight (NW) concrete. Both series had identical cross section geometry, reinforcements, span length, concrete strength, and FRP properties. The debonding strains of the lightweight and normal weight concrete are compared, and the validity ACI 440.2R-17 equation for lightweight concrete is evaluated.

Keywords: Lightweight Concrete, Debonding Strain, Strengthened T Beams, CFRP Sheets.

1041 - Bond between Flax-Trm and Masonry: Effect of Bond Length

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Abstract: The use of externally bonded composites for strengthening and seismic retrofitting of deficient structures is preferred to traditional systems, as they provide a time-efficient and less disruptive solution. Textile-Reinforced Mortar (TRM) systems, in which textiles are embedded in inorganic matrices, are commonly employed for unreinforced masonry structures due to their favourable mechanical properties and compatibility with various masonry substrates. Increased environmental awareness has recently brought researchers to focus on the use of more sustainable reinforcing materials, with minimal environmental impact, and to assess the potential of natural fibres and bio-composites in structural applications. However, the use of such innovative composite solutions as strengthening systems is limited and their bond behaviour to masonry has not been examined thoroughly.
This paper investigates the effectiveness of a Flax-TRM strengthening system for masonry structures and studies experimentally its bond behaviour. Fifteen single-lap shear bond tests were performed on masonry prisms strengthened with single-layer flax textiles embedded in lime-based mortar. Five different bond lengths (varying from 65 to 260 mm) were investigated. Preliminary results are summarised in terms of bond capacity, effective bond length and governing failure bond mechanism.

Keywords: bond, TRM, masonry, flax, natural fibres.

1098 - Experimental Evidences and Numerical Modelling of Srg Systems Under Uniaxial Load

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Abstract: Modern repairing and retrofitting methods for existing structures make use of composite materials, consisting of high strength textiles and a matrix, which can be either polymeric or inorganic.
These kinds of techniques are largely applied to masonry structures, since they significantly improve structural performance with a small increase of weight and a minimum invasiveness. However, the application of organic gluing agents on masonry has revealed some well-known drawbacks, which are almost all overcome resorting to inorganic matrixes, namely cement or lime mortars.
An entire class of composites has been thus identified as TRM (Textile Reinforced Mortars) or FRCM (Fibre Reinforced Cementitious Matrices). Among them, Steel Reinforced Grouts (SRG) are characterized by Ultra High Tensile Strength Steel (UHTSS) cords embedded in mortar matrix and their use to improve the structural performance of existing historical masonry buildings is becoming more and more diffused.
Qualification tests and acceptance criteria for SRG have been defined. SRG system has been studied in terms of mechanical characteristics, experimental application and documents on SRG properties and performances are actually available for both design and research purposes. A lot of work has been done but despite this, some aspects regarding the interaction between steel and mortar matrix systems need to be still investigated.
In this document the results of an experimental campaign carried out on different SRG systems obtained varying the number of cords, the density of steel textile and the typology of mortar matrix (lime based and cementitious) are presented. Experimental investigations have been planned by means of direct tensile tests and lap tensile tests.
Numerical simulations of direct tensile tests are also presented, aiming at identifying some peculiar aspects of the response of such a type of composite systems.

Keywords: SRG, Tensile behaviour, Overlap, Modelling.

1100 - Bond Behaviour of NSM Strengthening Systems on Concrete Elements Under Sustained Load and High Ambient Temperature

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Abstract: The study of the bond behaviour of FRP strengthening systems under service conditions has become increasingly important during the last years. Previous works have shown that sustained loading jointly with changes in environmental conditions may affect the long-term deformations of the FRP-concrete joint. Therefore, information from long-term tests under high ambient temperatures can provide relevant knowledge to fully understand the bond behaviour of the strengthening systems in real applications.
The main goal of this paper is to experimentally study the evolution of the bond behaviour of FRP-concrete joint with time under high service temperature, and how this progression affects the global slip of the strengthening system. For this purpose, an experimental programme of eight NSM pull-out specimens loaded with different levels of sustained load and under high ambient temperature was performed. Slip at the loaded end of the FRP was measured in order to capture its evolution with time.
From the short-term experimental campaign, an effect of the groove thickness and the bonded length on the maximum load and the failure mode were observed. Moreover, from sustained loading pull-out tests, a significant increase in the slip was observed during time. High effect of the bonded length and groove thickness on the slip at the loaded end was observed when specimens were subjected to high service sustained loading.

Keywords: CFRP, NSM, long-term conditions, high ambient temperature, sustained load.

1119 - A Comparative Study of Bond Test Methods for Externally Bonded FRCM and SRG Composites

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Abstract: The bond behavior of externally-bonded fiber reinforced composites has been studied experimentally using different types of test methods. In this study the bond behavior of composite strips externally bonded to fired-clay brick masonry was tested using single-lap direct shear tests and hinged beam tests. The results obtained from the two test types were compared to investigate the effect of the test set-up on the load-carrying capacity of the matrix-fiber interface. Two different composite systems were considered: a fiber-reinforced cementitious matrix (FRCM) composite with a balanced bidirectional mesh of basalt fibers embedded in a hydraulic lime-based mortar, and a steel reinforced grout (SRG) with a sheet of ultra-high-strength unidirectional steel fiber cords embedded in the same mortar. The results are discussed and compared in terms of failure modes and applied load versus slip of the fibers response. An estimate of the matrix-fiber interfacial fracture energy of SRG-masonry joints is proposed using a global energy balance approach that does not require measurement of the strain in the fibers.

Keywords: Bond, Fiber-Reinforced Cementitious Matrix (FRCM) Composite, Hinged Beam Test, Single-Lap Shear Test, Steel-Reinforced Grout (SRG) Composite.

1127 - The Role of Top Matrix Layer on the GTRM-to-Masonry Bond

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Abstract: This study aims to shed light on the role of a bond-related parameter that has received very little attention by the academia, namely that of individual mortar layers (bottom and top mortar layer in single-textile layer TRM configurations). To this purpose, single-lap/single-prim shear bond tests were carried out on masonry wallettes furnished with: (i) "conventional" TRM strips (the term "conventional" accounting for a single dry AR glass fiber textile strip sandwiched between two mortar layers, the bottom one bonded on the masonry and the top one); and (ii) "top mortar-less" TRM strips (that is, same as "conventional" ones but lacking their top mortar layer). Masonry comprised fair-faced solid clay bricks stack-bonded with a cement/lime general purpose mortar. The TRM strips were constructed using a cementitious mortar (based on Ordinary Portland Cement-OPC) and had a bond length equal to 250 mm which was larger than the effective one. Strains were measured along the central longitudinal fiber yarn by means of strain gauges. Digital Image Correlation (DIC) analysis was also conducted for some of the 'top mortar-less' specimens. The comparison of fracture energies of the two TRM configurations reveals that (for this type of TRM/substrate combination) the effect of the top mortar layer on the TRM-to-matrix bond characteristics is appreciable. Additionally, from the DIC analysis it is concluded that each load-aligned fiber yarn is activated along a length that varies among different yarns.

Keywords: GTRM; Masonry; Bond; Matrix Layers.

1179 - Tensile Tests of FRCM Coupons: The Influence of the Fiber-Matrix Bond Properties

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Abstract: Fiber-reinforced cementitious matrix (FRCM) composites are usually mechanically characterized by means of tensile and bond tests. The load responses provided by tensile tests of FRCM coupons are typically constituted of three phases, namely the uncracked, cracking, and fully cracked phase. Tensile tests can be performed by either transferring the force to the matrix (clevis- or clamping-grip test) or to the bare fibers (direct gripping of the fibers).
The bond behavior of FRCM composites is generally investigated using single-lap shear test setups, which allow for the evaluation of the stress-transfer mechanism within the matrix, at the matrix-substrate interface, and at the matrix-fiber interface. Within the framework of fracture mechanics, results of single lap shear tests allow a cohesive material law (CML) to be calibrated for the weaker interface that is activated during the test.
In this paper, a polyparaphenylene benzo-bisoxazole (PBO) fiber-matrix CML calibrated by the authors in previous works is introduced in an analytical model of FRCM tensile tests in order to verify if it allows the cracking process to be accurately predicted. The model allows for the introduction of different boundary conditions reproducing the different tensile test setups listed above. In particular, the boundary conditions associated with the gripping of the bare fibers are employed in this work and the results of the model are compared with experimental results of tensile tests of the same FRCM composite employed to calibrate the CML.

Keywords: FRCM composites, tensile response, cohesive material law, analytical model, cracking.

1218 - Bond Performances of SRG Composites: Experimental and Numerical Investigation

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Abstract: The Steel Reinforced Grout (SRG) composite system represents a newly developed promising technique for strengthening existing reinforced concrete and masonry structures. The SRG composite was comprised of steel fiber strips embedded within two layers of inorganic matrix. Nevertheless, the matrix is responsible for the stress-transfer in composites. The experimental results present in literature show a slippage of the fibers and fracture of the external matrix layer at the fiber-matrix interface. This is a critical phenomenon in structural strengthening applications.
The present paper presents the results of an experimental and numerical investigation on the bond performances of the SRG system bonded to concrete substrate. The FE analysis was developed using Abaqus-code with a bond slip model present in literature. In addition, the aim of the FE analysis was to predict the behavior of concrete joints strengthened with SRG composites. The parameters of the bond slip model law were calibrated on the results of the experimental campaign. The experimental campaign was focused on the concrete joint strengthened with SRG, in particular, the tests were conducted by a single lap direct shear test varying the bonded length. Finally, the comparison between the numerical and experimental curves was carried out in terms of peak load.

Keywords: Numerical model, SRG, Direct shear test/bond, Concrete joints.

1221 - Effect of Groove Depth on Behavior of CFRP Sheets Bonded to Heat-Damaged Concrete by Using EBROG Method

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Abstract: There is substantial need to strengthen heat-damaged concrete. One possible method is to retrofit the concrete with fiber reinforced polymer (FRP) composites. However, the heat-damaged concrete may express poor performance in bond between FRP and concrete. To overcome this issue, externally bonded reinforcement on grooves (EBROG) method was investigated in this study to improve the bond behavior of carbon FRP sheets to heat-damaged concrete. Concrete blocks were initially exposed to elevated temperatures by using a pre-defined heating protocol. Externally bonded reinforcement (EBR) method and EBROG method were utilized to strengthen the heated concrete. Single lap shear experiments were performed on FRP-retrofitted post-heated concrete specimens. Experimental results demonstrated that using EBROG method significantly improved the bond behavior, compared to the EBR method. More importantly, the groove dimensions affect the bond strength. By using different groove depths of 5, 10, and 15 mm, the maximum bond strength was experienced for depth of 10 mm.

Keywords: EBROG, CFRP sheet, bond behavior, heat-damaged concrete, groove depth.

1277 - Testing vs Application Issue for Fiber Reinforced Materials

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Abstract: The strengthening of masonry structures is nowadays performed by means of High-strength fibers embedded in inorganic matrix (Fiber Reinforced Cementitious Mortar materials, FRCM). In such materials lime or cement-based matrix is used instead of epoxy adhesive to reduce debonding issues between substrate and matrix, however some sliding phenomena and cohesive failures between fibers and the matrix mortar can occur. The main aim of this research is to examine the impact on the FRCM efficiency of the mechanical properties of fiber and matrix and potential geometrical defects, which are possible in real field applications. Discussion is based on the predictions obtained through an analytical model recently developed by the authors to investigate the local effects of adherence that affect the mechanical behaviour of FRCMs.
The topic is particularly important and greatly discussed in the scientific community and among manufactures and practitioners, because the bond test has a significant role, as it is used for the qualification of the material, providing sometimes very scattered results.
The model represents an attempt to reproduce the variability typically found in the experimental bond tests performed on FRCM systems for qualification purposes and to find solution to reduce this scatter and, overall, correlate this scatter to the performance in real application. The model was then applied to the typical cases of PBO-FRCM and Glass-FRCM to analyse slip and stresses in the bundle and in the matrix for different defects due to application issues.

Keywords: FRCM, cementitious matrix, fiber, strengthening system, bond behaviour

1280 - An Experimental Investigation on the TRM to Masonry Bond Under Fatigue Loading

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Abstract: Textile reinforced mortars (TRM) have been proven to be an excellent technique for the strengthening of unreinforced masonry walls providing increased flexural and shear resistance. TRM - also termed Fabric Reinforced Cementitious Matrices (FRCM) - involve high strength fibre textile materials impregnated in inorganic cement or lime based mortars. As in every externally bonded strengthening technique/material, one of the key parameters controlling the effectiveness of the TRM is the bond strength of the TRM to the masonry interface. Over the past fifteen years or so, the mechanics of TRM to masonry bond have been investigated experimentally, analytically, and numerically for the case of quasi-static loading. Conversely, the case of fatigue loading has not garnered much attention. Experiments conducted on FRP strengthened concrete specimens have however demonstrated the detrimental effect of fatigue to the corresponding interfacial properties. In this work, we present the preliminary results from an experimental investigation on the TRM to masonry bond strength under one sided cyclic loading conditions. In this experimental campaign, a series of single lap shear tests have been conducted on basalt textile fibre TRM bonded to masonry, considering various bond lengths.

Keywords: TRM, masonry, bond strength, fatigue.

1286 - Bond Behaviour of PBO FRCM on Curved Masonry Substrates

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Abstract: Fiber Reinforced Cementitious Matrix (FRCM) systems are generally fostered for applications on cultural heritage structures since they offer higher breathability and compatibility with precious masonry substrates. Historical masonry structures such as churches and palaces can often show curved elements that are inherently vulnerable to traction forces induced by overburden loads, moving supports or seismic actions.
Application of FRCM on curved substructures induces a reduced or enhanced bond capacity if the substrate is concave or convex and both mode I and mode II fracture energies can be involved.
In this study, a through experimental campaign was carried out to characterize a PBO-based FRCM system by means of uniaxial tensile tests on the single fibre bundles and on textile, as well as three-point bending and compression tests on the mortar matrix. To characterize the composite system, uniaxial tensile tests on composite coupons were carried out. Also, bond capacity of the system when adhered to straight bare bricks and curved masonry elements is investigated. The tested composite system demonstrates less susceptibility to sliding, when tightened due to the good balance between reinforcement ratio and textile spacing. Concerning bond behavior on curved supports, results show, as expected, that curved supports ease better bonding response due to the activation of radial confinement stress.

Keywords: PBO, single lap bond test, tensile test, curved masonry substrate

1289 - A Cohesive Contact Algorithm to Describe the Multi-Axial Bond Behavior of FRCM Composites

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Abstract: In the last decades, inorganic-matrix composites have been increasingly employed as externally bonded reinforcement (EBR) for masonry and reinforced concrete (RC) members. Among them, fiber-reinforced cementitious matrix (FRCM) composites, which are comprised of high-strength open mesh textiles embedded within inorganic matrices, showed promising results for both masonry and RC strengthening. FRCMs may include different types of fiber, such as glass, carbon, basalt, polyparaphenylene benzobisoxazole (PBO), and steel, and various matrices, such as cement-based, lime-based, and geopolymers. Acceptance criteria for material qualification and design guidelines have been recently published in Europe and US. FRCMs can still be considered as relatively-new materials and the current guidelines are just a starting point. More research is needed to fully understand the behavior of structural elements strengthened with FRCM. When a single layer of fiber textile is employed, failure of FRCM-strengthened elements occurs due to debonding at the matrix-fiber interface, although different failure modes can be observed when a different number of textile layers is used. Depending on the type of application and strengthening configuration, the composite can be subjected to a multi-axial state of stress that affects the response of the strengthened member.
In this paper, a three-dimensional cohesive contact algorithm is developed to accurately describe the bond behavior of FRCM composites subjected to a multi-axial state of stress. The algorithm accounts for the interaction (coupling) between the shear and axial stresses at the interface where debonding occurs. The cohesive contact algorithm is implemented in a finite element code that is employed to calibrate and model the matrix-fiber interface cohesive laws of a PBO FRCM composite.

Keywords. finite element model, cohesive interface, FRCM, mixed-mode, fracture mechanics

1295 - Carbon nanotubes strengthened interphase in Textile Reinforced Mortar (TRM) composites

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Abstract: Performance of inorganic matrix composite materials for structural purposes is strongly dependent on the matrix-to-fabric interphase bond strength. Consequently, owing to lack of congruence between the fabric and the matrix, design performance parameters are strongly penalised. Besides, yarn inner filaments (the core) easily slide over outer filaments (the sleeve) in the so-called telescopic failure. Broad experimental evidence supports the adoption of epoxy coatings to improve matrix-to-fabric strength and prevent telescopic failure, although the presence of the organic phase partially impairs the remarkable advantages associated to the inorganic matrix, such as thermal stability and water vapour permeability. Silica coatings appear as a promising alternative to traditional epoxy, by inducing localised pozzolanic reactivity, firmly linking synthetic fibres and hydraulic lime through the formation of highly cementing products at the interphase. In this work, the effect of a dispersion of multi-walled carbon nanotubes (MWCNT) in a silica nano-coating is assessed in uni-axial traction tests. The silica coating is prepared through sol-gel deposition in which carbon nanotubes are dispersed. The overall amount of carbon nanotubes in the silica sol is fixed at 0.5% wt. Silica-coated AR-glass and carbon fabric composite specimens, embedded in a commercially-available lime mortar matrix, are tested and compared. Carbon nanotubes provide a remarkable enhancement in both ultimate strength and elongation for AR-glass TRM, yielding an impressive two-fold increase in terms of strength. Differently, coated carbon fabrics composites show an increase up to 31% in terms of ductility, in view of an unexpected strength loss.

Keywords: Textile Reinforced Mortar, Silica nano-coating, Carbon nanotubes, mechanical performance.

1315 - Understanding Degradation of Fiber/Matrix Interface under Environmental Effects using Molecular Simulation

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Abstract: With promising mechanical properties, fiber reinforced polymer (FRP) composite has increasing applications in civil engineering, such as external strengthening material for building structures, and load-bearing component and internal reinforcement for new constructions. During intended service-life, the composite is inevitably exposed to changing environments with high levels of temperature, humidity, and ions, and the interfacial degradation between fiber and matrix becomes a critical problem, which leads to interfacial debonding and consequent composite degradation. In order to predict the long-term performance of composite material, it is important to understand the interfacial degradation between fiber and matrix under environmental effects. As a bottom-up approach, molecular dynamics simulation enables the molecular modeling of fiber/matrix interface and the simulation of molecular interactions occurred in local interfacial region, which contributes to the understanding of interfacial degradation under different environment exposures. In this work, recent research progress in understanding the environmental effects on the bonding degradation of fiber/matrix interface from a molecular level is presented. Based on the developed interface models, the variations of molecular structure and related degradation of interfacial properties under different environmental exposures are discussed, and the molecular interactions at the interface are investigated to explore the underlying mechanism. Furthermore, future research direction involving the development of fiber/matrix interface model for further characterization of the interfacial degradation is also provided.
Keywords: Fiber Reinforced Polymer, Fiber/Matrix Interface, Degradation, Environmental Effect, Molecular Dynamics.

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MINI SYMPOSIUM ON REINFORCING AND STRENGTHENING STRUCTURES USING PRESTRESSED FRP

1003 - Assessment of UHPC Bonded with FRP Bars

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Abstract: The bond of glass fiber reinforced polymer (GFRP) and basalt fiber reinforced polymer (BFRP) bars embedded in ultra-high performance concrete (UHPC) is experimentally examined. This state-of-the-art concrete is mixed with steel fibers (2.3% by volume) and silica fume in addition to high-early strength cement, water, silica sand, and a high-range water reducer. Specifically, silica fume to cement ratios range from 20% to 40%. The topography of the reinforcing bars, measured in accordance with a standard method specified by the American Society of Mechanical Engineers (ASME), indicates that GFRP has fluctuating elevations, while BFRP possesses a flat surface. Push-out bond tests characterize the failure modes of the UHPC-GFRP and -BFRP interfaces as well as their energy dissipation values. The amount of silica fume affects the load-bearing capacity of the interface, irrespective of bar type. Microscopic analysis exhibits residual resins, after the failure of the interface, and clarifies the influence of steel fibers on the bond between the concrete substrate and reinforcement.

Keywords: bond, fiber-reinforced polymer (FRP), interface, ultra-high-performance concrete (UHPC).

1004 - Stochastic Modeling for Time-Dependent Behavior of CFRP-Prestressed Concrete Girders

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Abstract: The time-dependent behavior of prestressed concrete bridge girders with steel strands and carbon fiber reinforced polymer (CFRP) composite tendons is analytically investigated. A stochastic modeling approach, Polynomial Chaos Expansion (PCE), is employed to address uncertainties associated with the girder responses. According to the American Association of State Highway Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications and ACI 440.4R-04, three girders (BT-54, BT-63, and BT-72) are designed and their behavior is examined. To compare the performance of the steel-prestressed concrete girders against that of their CFRP counterparts, corrosion is simulated for 100 years. The prestress loss of the steel-prestressed girders subjected to damage is noticeable, whereas the loss of the CFRP-prestressed girders is stable over time. The variation of the load-carrying capacity of the girders is affected by the section depth, irrespective of tendon type. Currently, research is underway to evaluate the deformability, deflections, and sectional rotations of the girders.

Keywords: carbon fiber-reinforced polymer (FRP), prestress, stochastic modeling

1021 - Flexural Behaviour of RC Beams Strengthened with Post-Tensioned CFRP Strips with Various Prestressing Level

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Abstract: The paper presents the results of the research on a series of reinforced concrete beams strengthened with the new Polish CFRP post-tensioning system with various prestressing levels (force). The tests included four RC beams with a rectangular cross-section of 0.50 m × 0.42 m and a length of 6.0 m. The first beam was a reference (control) beam. The next three beams were strengthened by prestressing with two CFRP strips. Prestressing level is defined as a ratio of prestressing force to the characteristic ultimate tensile strength of CFRP strip. Tested beams were prestressed with 30%, 40% and 50% of CFRP tensile strength which corresponds to a force of 162 kN, 216 kN and 268 kN for subsequent beams. The beams were investigated in a full range of flexural behaviour, including post-debonding phase. The results indicate that changing of prestressing level has a significant influence on behaviour of prestressed beams. The beams strengthened with higher prestressing level exhibited a higher cracking, and steel-yielding moments as well as slightly higher level of CFRP utilisation. Changing the strip prestressing level did not affect the load-bearing capacity of the beams. Beams with different prestressing levels exhibited similar flexural behaviour until strip debonding. Differences occurred in post-debonding phase of work. The higher prestressing level, the failure mode of the beams was more sudden. On the basis of the failure mode of the tested beams, the optimal prestressing level of the CFRP strip in the new prestressing system was determined.

Keywords: CFRP strips, prestressing level, RC beams, strengthening system.

1128 - Load Deflection Behaviour of Self Consolidating Concrete Beams Prestressed with CFRP Bars

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Abstract: Self-consolidating concrete (SCC) offers several potential benefits that derived from its unique flow characteristics: improved productivity and quality of concrete construction. The current ACI 440.4R-04 design guidelines does not account for SCC in flexural deflection predication of beams prestressed with Fibre Reinforced Polymers (FRP) bars. This paper presents results of flexural testing of four beams prestressed with 12.7 mm Carbon FRP bars. Two beams made from SCC and two beams made from normal vibrated concrete NVC. The prestressing levels were 30% or 60% of the guaranteed tensile capacity of the CFRP bars. Beams were tested under a four-point static bending load under displacement control. Measurements of load, midspan deflection, strain in CFRP bars and in the concrete were collected using a data acquisition system. Results was compared to two methods for flexural deflection predictions: simplified method based on (ACI 440.4R-04), and detailed analytical method from literature. The simplified method was based on effective moment of inertia approximation while the detailed method was based on effective moment of inertia and effective centroid calculations. In both methods, the actual concrete modulus of elasticity was used. Prediction of the midspan deflection based on the simplified method for SCC beams was unconservative after cracking. The experimental results correlated well with the detailed method at higher loads range for both types of concrete.

Keywords: Self Consolidating Concrete. Prestressed Beams. CFRP

1172 - Effect of FRP Anchor Inclination Angle on Shear Strengthening of Reinforced Concrete T-beams

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Abstract: The purpose of this paper is to study the effect of anchoring carbon fiber-reinforced polymer (CFRP) U-Wrapped laminates by CFRP splay anchors to strengthen shear deficient reinforced concrete (RC) T-beams. Recent investigations in this field has proved that CFRP anchors could delay or prevent debonding of CFRP laminates. However, few tests were conducted to study the effect of the FRP anchors on the strength and ductility of RC beams externally strengthened in shear with CFRP sheets. In addition, there are no design guidelines for the anchors in the current strengthening design codes of practice. For the aforementioned reasons, one-point loading tests were conducted on six shear deficient RC T-beams. Five specimens were strengthened with U-Wrapped CFRP laminates, four of which were anchored with different configurations of CFRP splay anchor systems, and one T-beam was left unstrengthened to serve as a benchmark specimen. The parameter investigated in this study is the anchor inclination angle. The angles examined are 0º, 25º, 45º, and 90º, respectively. Test results showed that the anchors delayed CFRP debonding, improved the shear strength, and significantly enhanced the ductility of the unanchored RC beam specimen. In addition, small anchor inclination angles performed better in terms of enhancing the shear strength and ductility of RC T-beams than perpendicular anchors. This study will contribute in the development of design recommendations of FRP anchor splay systems.

Keywords: CFRP, U-Wraps, FRP anchor, shear strengthening, RC T-beams.

1201 - Experimental Study on the Static and Fatigue Behaviour of a New Mechanical Wedge-barrel anchor

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Abstract: Post-tensioned steel strands have been traditionally used in different prestressed structures such as concrete girders, post-tensioned concrete slabs, cable-stayed bridges, post-tensioned walls, etc. for a long time. However, due to the vulnerability of steel to the fatigue and corrosion, application of carbon fiber reinforced polymer (CFRP) rods, because of their higher strength-to-weight ratio, corrosion and fatigue resistance, is a good substitution for prestressed steel strands. Nevertheless, it is a major challenge to develop a purely mechanical anchorage for CFRP rods. In this study, a new mechanical anchorage for prestressed CFRP rods is introduced. The proposed anchor consists of a steel barrel with a conical hole and three separate aluminum wedges being in direct contact with the CFRP rod. The anchor system transfers the load through friction, without any adhesive required. The static and fatigue behavior of the anchor were experimentally investigated, following the Guideline for European Technical Approval of Post-Tensioning Systems (ETAG 013). The effect of various parameters such as friction between the wedges and the barrel and between the wedges and the CFRP rod and the level of the presetting force on the static and fatigue performance of the anchors were experimentally studied. In the static tests, the load carrying capacity of the post-tensioned system was much higher than the guaranteed strength of the CFRP rods. The fatigue tests indicate that no slippage occurs between different components of the anchor system during the cyclic loadings, and, no damage is accumulated in the system after 2 million cycles. In addition, it was observed that the high frequency of cyclic loadings does not affect the cyclic performance of the system; i.e. under high loading frequencies, no heat was generated in the anchor, since the components did not have any relative movements.

Keywords: Wedge-barrel anchor, CFRP rod, Post-tensioning, Fatigue.

1212 - Iron-Based Shape Memory Alloy (FE-SMA) Vs. CFRP for Prestressed Strengthening of Civil Metallic Structures

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Abstract: Iron-based shape memory alloy (Fe-SMA) is a smart material that has been recently engineered and developed for civil engineering applications. The Fe-SMA has become a new reinforcement material for prestressed-strengthening of structures. This article aims to provide the first systematic study on the comparison between these two reinforcement materials with a particular emphasis on conditions imposed in civil engineering. The production procedure, mechanical properties, fatigue, creep/relaxation, corrosion, thermal expansion, high-temperature and fire behavior of the Fe-SMA in comparison with those of carbon fibre-reinforced polymer (CFRP) material are discussed. In the next step, the static and fatigue behavior of different structural components strengthened by prestressed CFRPs or activated Fe-SMAs are explained. Finally, a cost analysis is carried out to compare the two strengthening solutions (with Fe-SMA and CFRP) for prestressed-strengthening of 6.4-m girders. The cost comparison revealed that although the current price of the Fe-SMA strips is higher than that of the normal modulus CFRP plates, both of the strengthening solutions are found to be almost equivalent from a cost-performance point of view, when the achievable prestressing force and the cost of the mechanical clamping systems are taken into consideration.

Keywords: Prestressed strengthening, CFRP composite, Fe-SMA reinforcement, high-cycle fatigue, cost comparison

1222 - Effect of Groove Depth on Behavior of Prestressed CFRP Strips Bonded to Concrete by Using EBROG Method

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Abstract: The efficiency of externally bonded reinforcement on groove (EBROG) method to improve the bond behavior of non-prestressed fiber reinforced polymer (FRP) composites to concrete has been so far demonstrated in several research studies. Recently, the performance of EBROG method has been investigated to enhance the bond resistance of prestressed FRP strips to concrete. In the current study, the influence of groove depth on bond behavior was examined. For this purpose, EBROG method with various groove depths was used to strengthen concrete prisms and its performance was compared with that of the conventional externally bonded reinforcement (EBR) method. Prestress force-release tests were conducted to study the bond behavior of prestressed carbon FRP (CFRP) strips to concrete. Experimental results showed that the bond resistance of EBROG joints increased to more than 200%, compared to that of the EBR joints. EBR joints exhibited an average bond resistance of 34.4 kN, while EBROG method with 10 × 5 and 10 × 10 mm (width × depth) groove dimensions led to average bond resistances of 72.0 and 81.4 kN, respectively. Therefore, for the grooves dimensions used in this study, it can be concluded that the deeper the grooves, the higher the bond resistance in a prestress force-release test. In addition, it was observed that the failure in EBR and EBROG was governed by the debonding of the prestressed strip from the concrete substrate. However, when EBROG method was used, cracks were developed in concrete depth and width, outside the bond area. Considering the failure plane in each specimen, an analytical procedure was proposed to predict the bond resistance of prestressed CFRP strips to concrete. Good agreement was observed between the proposed analytical model and the experimental results.

Keywords: EBROG, prestressed CFRP strip, bond behavior, groove depth.

1290 - Novel Wedge Anchorage for CFRP Plates

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Abstract: Strengthening degraded concrete structures with carbon fiber reinforced polymer (CFRP) is a practical and an economical alternative to the total replacement of structures. Prestressing CFRP plates is one of the efficient solutions used to utilize the high strength of CFRP plates to improve the performance of concrete structures. In order to prestress a CFRP plate, anchorages are required to grip the plate at its both ends. However, anchoring a CFRP plate is a challenging task due to its vulnerability to lateral loading. Hence, a novel compact wedge anchorage system for CFRP plate was developed and tested. The wedge anchorage is composed of an outer cylindrical steel barrel, two steel wedges, and two soft copper plates. The performance of the wedge anchorage was experimentally investigated under tensile loading. Two different presetting levels were applied: high presetting using a hydraulic press and low presetting by manual hammering. The reliability of the wedge anchorage was illustrated by successfully gripping the CFRP plate until its full tensile strength was attained. The reusability of the wedge anchorage was demonstrated by its consistent performance throughout the repeated tests.

Keywords: CFRP Plate, Concrete Strengthening, Presetting, Prestressing, Wedge Anchorage.

1343 - Strengthening of Concrete Structures Using Prestressed FRP – A Review

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Abstract: Fibre-reinforced polymers (FRP) reinforcement has been used for flexural strengthening either as an externally bonded (EB) system in the form of FRP laminate (sheets, plates or strips) applied to the tension side of reinforced concrete (RC) members or as a near-surface mounted (NSM) system. The NSM system is composed of an FRP strip or bar embedded inside a pre-cut groove filled with epoxy. The groove is made into the concrete cover at the tension side of the RC member.

Although flexural strengthening using non-prestressed FRP reinforcement increases the ultimate strength of a member, it does not significantly improve the member performance under service loads (i.e. it does not increase the stiffness of the member under service loads). This is because non-prestressed FRP strengthening is a passive strengthening technique where the FRP remains inactive until additional loads are applied. To increase the stiffness of the member, the strengthening system must be active rather than passive. Active strengthening is achieved by prestressing the FRP reinforcement before being bonded to the concrete. The advantages of prestressed FRP strengthening are (i) more effective use of the material because a greater portion of its tensile capacity is employed, and (ii) the FRP material contributes to the load-bearing capacity under both service and ultimate conditions. Prestressing the EB and NSM FRP requires a special anchorage system that should be practical in implementation.

In general, prestressing is used to enhance the flexural behaviour of reinforced concrete members under service loads, especially in bridges and beams with large spans. There is a limitation on the deflection and serviceability conditions. Because of their high tensile strength properties, FRP materials have significant advantages for use in prestressing and post-tensioning strengthening applications. The specialized application of prestressing the FRP reinforcement for flexural strengthening of structures combines the non-corrosive and lightweight benefits of the FRP reinforcement with the advantages associated with external prestressing. However, the challenging part of the active FRP strengthening system is applying prestressing force to the FRP material using a suitable practical anchorage and prestressing system.

The paper presents a review of the state-of-art research related to (i) the anchorage systems developed to prestress EB and NSM FRP with the focus on the practicality of the prestressing systems where the FRP is prestressed against the member itself, and (ii) the performance of members strengthened using prestressed FRP reinforcement.

Keywords: Active, Anchorage, Flexural, Prestressing, Externally Bonded, Near-Surface Mounted.

1391 - Experimental Investigation of a Novel Circular Anchor System for Prestressed CFRP Plates

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Abstract: Prestressed carbon fiber reinforced polymer (CFRP) system has been extensively studied and applied in strengthening industry. Various anchor systems have been developed to prevent premature failure of prestressed CFRP composites. Current prestress CFRP anchor system are classified as epoxy based and mechanical anchors. Most anchoring systems are designed for thin or narrow CFRP plates. The anchoring efficiency of large cross-section CFRP is very limited. It is imperative to develop an effective, easy installable anchor system for relative large cross-section CFRP plate. Under this background, a novel circular wedge anchoring system was developed and tested for popular 3*50 mm prestressed CFRP plate. This paper presents an experimental investigation of the proposed anchor system, mechanical performance and applicability are discussed and reported. Test result showed that material property, tooth pattern, and wedge angle have notable effect on failure modes and anchor capacity. The high capacity, small dimension, light weight and convenient installation characters of the proposed system contributes future promotion of prestressed CFRP strengthening technology.

Keywords: Presstressed CFRP, anchor system, circular wedge, experimental tests.

1392 - Numerical Analysis of a Novel Circular Anchor System for Prestressed CFRP Plates

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Abstract: Prestressed carbon fiber reinforced polymer (CFRP) has been proved effective on flexural strengthening and crack repairing of reinforced concrete beams. Various types of anchor systems were develop for prestressing CFRP composites. However, few studies were conducted for thick and wide CFRP plates. Under this background, a novel circular anchor system for popular 3 by 50 mm CFRP plates was developed and tested. Experimental results showed that the novel circular anchor system had a capacity of 297 kN, which is higher than those with small sections, and a 80% usage of CFRP tensile strength was achieved. The capacity of circular anchors is significantly affected by magnitude of interference, tooth pattern and wedge angles. A non-linear finite element model was developed to investigate mechanical performance of circular anchor system. Parameter study was performed to optimize the design of the new anchor system. Numerical results showed that wedge angle and tooth pattern dominated the failure mode and anchor strength of circular shaped anchor system.

Keywords: Presstressed CFRP, anchorage system, circular wedge, numerical analysis.

MINI SYMPOSIUM ON STRENGTHENING OF STEEL STRUCTURES

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1030- CFRP Strengthening and Long-term Wireless Monitoring of an Old Roadway Steel Bridge: First Application in Australia

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Abstract: This article presents an overview of the carbon fiber-reinforced polymer (CFRP) strengthening and wireless sensor network (WSN) monitoring of an old metallic roadway bridge in Melbourne, Victoria, Australia. A flat pre-stressed un-bonded reinforcement (FPUR) system was developed to apply pre-stressed CFRP plates to the steel cross girders of the Diamond Creek Bridge. The bridge is a 121-year-old metallic roadway bridge, which is subjected daily to passenger vehicles and heavy trucks. Sets of laboratory tests were performed to examine the efficiency and fatigue performance of the proposed FPUR system prior to its installation on the bridge. Furthermore, in order to demonstrate the efficiency of the proposed retrofitting technique, the bridge was instrumented with various types of sensors (including strain gauges, and temperature and humidity sensors) and short- and long-term measurements were performed. For short-term measurements, the bridge was loaded using a 42.5-ton semi-trailer before and after strengthening. For long-term monitoring, a WSN system was used to monitor the pre-stress level in the CFRP reinforcement since its application in late 2017. The CFRP plates were pre-stressed up to about 980 MPa (≈ 38% of the CFRP tensile strength), which resulted in an approximately 50% reduction in the maximum tensile stress in the bottom flanges of the strengthened I-girders. The short- and long-term measurements in this study demonstrate that the proposed FPUR system is very effective for flexural and fatigue strengthening of such bridge girders.

Keywords: Carbon fiber-reinforced polymer (CFRP), prestressing, wireless sensor network (WSN), structural health monitoring (SHM), steel bridges.

1050 - Rapid SIF Calculation of Inclined Cracked Steel Plates Bonded with CFRP Materials, Prestressed and Non-prestressed

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Abstract: Stress intensity factor (SIF) is a fundamental parameter in evaluating the fatigue crack propagation of steel structures. This paper focuses on the theoretical SIF calculation of steel plates with an inclined crack, subjected to tensile fatigue loading. Erdogan and Sih's equations for calculating the mixed-mode I/II SIF are extended to the bonded strengthening of steel plates using non-prestressed and prestressed CFRP. The prestress loss caused by the compression of the steel plate is considered. The theoretically calculated SIFs are proven to be in very good accordance with the numerical simulation. Due to the fact that all mixed-mode fatigue cracks develop soon to the tensile predominant mode under tensile fatigue loading, a simplified method is proposed for fatigue life estimation, in which the cracks propagate under mixed-mode in the very beginning and then perpendicular to the loading direction. The simplified method shows a fairly good capability of the fatigue life estimation.

Keywords: Stress intensity factor (SIF), carbon fiber reinforced polymer (CFRP), fatigue life, inclined crack, prestress, unbonded and bonded fatigue strengthening.

1054 - Durability of Structural Adhesive Exposed to Marine Environment

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Abstract: Structural adhesive plays an important role in external bonding with fibre-reinforced polymer (FRP) materials for strengthening aged steel structures. The durability of structural adhesive exposed to harsh environmental conditions has attracted much attention in recent years. Extensive work has been conducted on the performance of different structural adhesives when immersed in distilled water, salt solution, alkaline solution and so on. Several prediction models for moisture absorption and mechanical behaviour degradation have been proposed based on test data. However, the effect of chloride ion has not been well understood. This paper conducted an experimental study on the durability of structural adhesive when subjected to marine environment with a special focus on the influence of chloride ion. Two types of structural adhesive were selected. A total of 256 samples were prepared and exposed to various conditions, including simulated seawater and distilled water at 35 °C and 50 °C. The moisture absorption and mechanical properties degradation of adhesive were carefully monitored. Based on the experimental data, an index was developed to represent the effect of chloride ion.

Keywords: Structural adhesive, durability, chloride ion, marine environment.

1202 - Development of a Strengthening System for Riveted/Bolted Steel Connections using Prestressed CFRP Rods

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Abstract: Among different details in old riveted railway bridges throughout the world, connections such as stringer-to-floor-beam double-angle connections are one of the most fatigue-prone details. These connections are subjected to fatigue loadings due to the secondary out-of-plane deformation. However, there are only few traditional strengthening techniques that are proved to be not so effective in permanently addressing the fatigue issue. In this study, a novel un-bonded prestressed retrofitting solution is proposed for strengthening riveted/bolted steel angle connections. The strengthening system consists of prestressed carbon fiber reinforced polymer (CFRP) rods, which are clamped at the ends using mechanical wedge-barrel anchors. The prestressing force of CFRP rods are transmitted to the strengthened member using the clamps functioning purely by friction. Therefore, an adhesive bonding is not required, and, no damage is imposed to the parent structure. The installation procedure consists of two main stages: presetting the wedges into the barrels, and, prestressing the CFRP rods. For the presetting, a novel method is introduced, making it possible to apply high presetting forces on-site. The application of prestressing force is done by pumping the hydraulic jacks. The static behavior of the strengthening system is experimentally investigated through pull-off tests. In addition, the fatigue behavior of the strengthening system is studied by the laboratory tests on stringer-to-floor-beam double-angle connections. Furthermore, stress distribution in the clamping system and connected parts was analyzed using a Finite Element (FE) model leading to final design of the system.

Keywords: Prestressed CFRP rod, Post-tensioning, Wedge-barrel anchor, finite-element (FE).

1220 - Durability Behaviour of Notched Steel Beam Strengthened with Prestressed CFRP Plate

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Abstract: Strengthening deficient steel structures using prestressed Carbon Fibre Reinforced Polymer (CFRP) would be a promising technology. Fatigue loading and hygrothermal exposure can weaken the adhesive bonding, thereby affecting the durability behaviour of the strengthened structures. In this paper, the prestress loss and flexural performance of strengthened steel beams subjected to fatigue damage (FD) and wetting/drying cycles (WDCs) were experimentally investigated. The prestress loss after WDCs exposure is less than 60.8 με, indicating the effectiveness of the end anchorage system. The FD, WDCs, and the combined effects have a slight influence on the stiffness and load capacity of the strengthened steel beams. However, the debonding initiation is greatly affected by FD and WDCs for strengthened steel beams, and further degradation can be found for strengthened steel beam subjected to the combined effects. Moreover, the ultimate CFRP utilization ratio remains above 90% for prestressed beams even subjected to the combined effects.

Keywords: CFRP, notched steel beam, prestress loss, wetting/drying cycles, fatigue damage, flexural behavior.

1245 - Computational Investigation of Mode-I Fatigue Crack Growth in CFRP-Strengthened Steel Plates with a Cohesive Zone Model

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Abstract: An increasing number of existing steel structures are nowadays at the end of their service lives and most of them are subjected to fatigue loading. To tackle the fatigue problem, carbon fiber-reinforced polymer (CFRP) composites have been proposed and successfully used as an alternative and efficient technique to strengthen fatigue prone (damaged) steel structures. Experimental studies on different CFRP strengthening systems (bonded and unbonded) showed also that using prestressed unbonded CFRP reinforcement could further enhance the performance of the strengthening system and promotes crack arrest. Different models have been proposed to investigate fatigue crack growth of CFRP-reinforced steel structures. They mainly refer to empirical damage accumulation rules (S-N curves) and fatigue crack propagation models based on fracture mechanics concepts such as Paris' law or similar. As an alternative approach in this paper, the computational assessment of Mode-I fatigue crack growth in the unreinforced and CFRP-reinforced (nonprestressed bonded and prestressed unbonded) steel plates are studied by using a cohesive zone model (CZM). The comparison between numerical and experimental results validated the finite element modelling, which will be further extended to the investigation of crack propagation under mixed mode condition.

Keywords: Fatigue loading, Carbon fiber-reinforced polymer (CFRP) strengthening, Crack propagation, Cohesive zone model, Finite element method.

1264 - Fatigue Durability in Welded Gusset Joints Strengthened by Carbon Fiber Sheets Using VARTM Technique

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Abstract: This paper deals with the fatigue durability of typical welded gusset joints in steel bridges strengthened by externally bonded CF (carbon fiber) sheets using VaRTM (Vacuum assisted Resin Transfer Molding) technique. VaRTM is a composite fabricating technique, can be used to apply CF sheets on cracked steel structures. The strengthening operation work have been proven to be very efficient and convenient even on complex shapes of structures due to the flexibility of this method. Perfectly close contact particularly between weld beads and the CF sheets provides a great advantage on reduction of the high stress concentration which is usually occurred at the fillet weld toe at the end of gusset plate. The reduction of stress concentration at weld toe was analytically investigated, where the 3D FEA (finite element analysis) model was simulated from a number of image data taken from actual experimental specimens by digital camera. The target specimens of welded gusset plates were fabricated and subjected to cyclic load. The fatigue tests of two types of specimens, non-strengthening and strengthening specimens using VaRTM technique have been conducted. The strengthening specimens are prepared with 23 layers of CF sheets (high-strength type), equivalent to reduction of stress concentration of approximately 1/3. Furthermore, in order to prevent the debonding of adhesive at CF sheet end, taper is designed under condition of fatigue limit of adhesive using theoretical calculation. The strengthening effects have been evaluated under applied nominal stress ranges, converted nominal stress range and hot-spot stress range experimentally. The result shows that the fatigue durability of welded gusset joints strengthened by CF sheets using VaRTM technique can be remarkably improved, reaching fatigue limit (10 million cycles) and over JSSC-A grade.

Keywords: Strengthening, welded joints, fatigue durability, VaRTM technique, CF sheets.

1282 - Iron-based Shape Memory Alloy Strengthening of a 113-Years Steel Bridge

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Abstract: This paper presents an application of iron-based shape memory alloy (Fe-SMA) for the strengthening of metallic girder of a historical roadway bridge in Petrov nad Desnou, Czech Republic. This is, to the best of author´s knowledge, the first application of Fe-SMA for strengthening of bridge structure worldwide, as the previous applications were mainly on building structures. The shape memory effect (SME) of Fe-SMA was used for prestressing of the steel girder. The SME is material property of deformed Fe-SMA to return to its original shape upon heating and subsequent cooling. A mechanical anchorage system was developed to apply pre-strained Fe-SMA plates to the steel girders of the 113 years old bridge, which is daily subjected to passengers and heavy vehicles. The SME in the Fe-SMA was then activated by heating to approximately 260 °C using heating ceramic pads. The test results showed that achieved recovery stress of the Fe-SMA strips led to a maximum compressive stress of -33 MPa in the lower flange of the steel girder. This compressive stress could significantly increase the yield and fatigue strength of the strengthened girder. Before and after the strengthening, the bridge was loaded with a 45.34-ton crane. Prior to installation of the strengthening to the bridge a static test was performed in the laboratory to examine the efficiency of the proposed strengthening method.

Keywords: Shape memory alloy, shape memory effect, strengthening, historical steel bridge.

1432 - Study On Buckling Behavior Of Prestressed Cfrp-Reinforced Steel Columns By Fem And Ann

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Abstract: Prestressed (PS) carbon fiber reinforced polymer (CFRP)-reinforced steel columns are novel multiparameter systems exhibiting complex nonlinear buckling behavior, which was investigated herein with the finite element method (FEM) and an artificial neural network (ANN). First, FEM models of the columns under axial and eccentric compression were built. The numerical and experimental results were in good agreement. Based on the validated FEM model, key parameters (CFRP initial prestressing force and supporting length) were studied, and the influencing rules on the buckling capacity and reinforcing efficiency of the reinforced columns were obtained. Then, 312 data sets from the validated FEM model covering 8 key parameters were generated using non-linear finite element calculation software ANSYS. Finally, as ANNs are good at handling highly complex and nonlinear problems, a practical ANN tool was developed for predicting the buckling capacity of PS CFRP-reinforced steel columns, which gives results with a high accuracy compared with FEM results.

Keywords: Steel column, CFRP, buckling, finite element method, artificial neural network.

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1102 - Definition of a Moisture Conversion Factor for the Durability Design of GFRP Materials for Civil Engineering Applications

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Abstract: The long-term performance of glass fibre reinforced polymer (glass-FRP, GFRP) materials used in civil engineering applications is influenced by several factors, such as their constituent materials, their production processes and quality level, and environmental factors, such as temperature, moisture, or ultra-violet radiation, among others. In the design of GFRP civil engineering structures it is important to ensure that the design values of material properties adequately account for the potential property reductions that may stem from ageing and exposure to environmental factors during service life. The first part of this paper presents an assessment of existing design guidelines for FRP structures regarding the recommendations they provide about the reduction of FRP mechanical properties due to moisture. The second part of the paper presents a survey of test data available in the literature concerning the effects of exposure to moisture in the mechanical properties of FRP materials with E-glass fibres and either unsaturated polyester or vinylester resins. The review comprised accelerated ageing tests carried out in water or saline solution immersion. The mechanical properties assessed included strength and moduli in tension, compression, and in-plane shear, as well as interlaminar shear strength. The third part of the paper compares the gathered experimental data with Arrhenius-type prediction models found in the literature, to ultimately derive a conversion factor to account for the material degradation in environments with high- and continuous exposure to moisture for a reference service life of 50 years, typical of civil engineering applications.

Keywords: GFRP materials, unsaturated polyester, vinylester, durability, moisture, conversion factor.

1209 - Multi-objective Design Optimization of Sandwich Panel

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Abstract: In the scope of an R&D project a new floor system based on sandwich panel has been developed. The lightweight structural system shall be a competitive solution when compared to traditional rehabilitation technique of degraded timber floors in old buildings. The layout of the sandwich prototypes designed involved the use of steel face sheet and: i) steel webs and polyurethane (PUR) foam core system; ii) glass fiber-reinforced polymer (GFRP) webs and PUR foam core system; and iii) outer steel webs and balsa wood core. The design of the sandwich panels included an optimization procedure. A multi-objective genetic algorithm (GA) was developed for this purpose as it is a search method well suited for the solution of optimization problems. The multi-objective GA aims at the minimization of the three objective functions, i.e. cost, mass and environmental footprint of the sandwich panel. The definition of the main feature of the algorithm includes consideration about encoding procedure, fitness scaling, selection method and handling of constraints. The boundary conditions are imposed so that the retrieved solutions will represent a feasible solution to the problem. These boundary conditions are the analytical formulation of the serviceability, ultimate limit state and thermal transmittance verifications imposed by the building codes to sandwich panels. The present paper deals with the introduction of all the aspects of the optimization problems providing as an example the optimization of the panel with steel face sheets, webs and PUR foam.

Keywords: Sustainability, Sandwich Panel, Multi-objective Optimization, Genetic Algorithm.

1210 - A Preliminary Design of a New Lightweight Floor System

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Abstract: A new lightweight floor system was developed to tackle the sustainability issue in the construction sector. The proposed flooring system is suited for rehabilitation of degraded timber floors in existing building. Despite the great potential that sandwich construction shows as load bearing elements their use has been hindered by the high initial cost. Three alternative architectures, all including cold-formed steel (CFS) face sheets, were envisaged, namely i) CFS webs and polyurethane (PUR) foam core system, ii) glass fiber-reinforced polymer (GFRP) webs and PUR foam system and iii) outer CFS webs and balsa wood core. The structural, thermal, acoustic and fire resistance requirements were identified in the Portuguese national codes. Particular attention is given to the description of the materials adopted for the different components with respect to the driving factors of the design of the panel, namely weight, cost, environmental impact, load bearing capacity, rigidity, thermal and acoustic properties and fire resistance. The preliminary design of the three sandwich panels is carried out considering the value of the actions established in the Eurocode standards. The final layout and cost estimate are the results of a parametric study aimed at retrieving the lightest and most economical solutions.

Keywords: Sustainability, Floor System, Sandwich Panel, Limit States Design

1227 - Determination of Creep Behaviour of Adhesively Bonded Assembly – Application to Adhesively Bonded Steel Fasteners

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Abstract: The use of adhesively bonded assembly is clearly justified for the case of all-FRP structures. Yet, there are still some issues related to the appraisal of the durability for such assembly. This article presents some investigations led on adhesively bonded connections in the case of steel fasteners bonded to steel plate. The studied solution was developed by Cold Pad to propose alternative assembly to welding or bolting (Figure 1). This allows avoiding heavy on-site operations and is particularly well adapted to applications requiring cold working. In addition, it prevents from local steel material fragilization, residual stresses creation, or geometrical stress concentration that may decrease the structure's life expectancy. The understanding of creep behavior may help in a greater appraisal of long-term behavior of bonded solutions in other cases, such as all-FRP structures for instance. To be able to investigate the creep behavior of the developed solution, both experimental and numerical investigations were carried out. The experimental investigations were led on real scale assembly, at different stress levels, and under different load situations. The fastener may indeed be submitted to either predominant tension load, or shear load. These investigations led at different load levels allowed obtaining failure modes, repeatability, time to failure data, but also, local displacements evolution with time. The results revealed a non-linear evolution of those displacements closed to a Burger law. This model was thus chosen, and an analytical determination of creep parameters was realized. This was compared to finite element investigations to verify the adequacy of the proposed methodology. The good suitability of the modelling approach is demonstrated, and the dependency of the parameters with stress level is highlighted. In addition, the finite element investigations allow giving insight of internal stresses evolution during creep.

Keywords: Adhesively bonded connections, creep behaviour, experimental investigations, modelling.

1231 - Influence of Hygrothermal Effect on the ModeIi Fracture Toughness of Epoxy Resins for Civil Engineering Applications

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Abstract: This paper presents the first experimental results relative to the study of the hygrothermal effect on the mode II fracture toughness of two commercial epoxy resins suitable for civil engineering applications. To this scope, adhesive joints (with adherents in Glass Fiber Reinforced Polymer - GFRP) for End Notch Flexure (ENF) test were produced. In particular, three different kinds of sample were considered: aging samples immersed in sea-water and tap-water at a constant temperature of about 30°C and unaging specimens.
The results here presented and discussed are the first ones (relative to an immersion time of six months) of a huge experimental program still ongoing consisting of 200 samples in total for an immersion time of fifteen months. The temperature of the water (about 30°C) was selected to be lower than the resins glass transition temperature evaluated through the variation of the specific heat capacity of the samples measured with Differential Scanning Calorimetry (DSC) analysis following ASTM E1356 Standard. Experimentally, it was observed an increase of the fracture energy in the first months followed by a decrement.
Parallel to the evaluation of the fracture energy in mode II, the water absorption of each kind of resin and GFRP adhesive sample was also investigated according to EN ISO 62:2008. The experimental results show that the equilibrium value of water absorption of both resins is reached in about one month, while that of GFRP samples depends on the type of liquid: three months for tap water and about 5 months for sea water.

Keywords: End Notch Flexure (ENF) test, water absorption, epoxy resin, Glass Fiber Reinforced Polymer (GFRP).

1354 - A Critical Look at the Current Status on the Design Regulations for Structural Adhesively Bonded Joints of Fibre Reinforced Polymers

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Abstract: Adhesive bonding is widely recognised as a key technology in many industries, including in particular where composite materials are in the focus. Contradicting this statement is the fact that adhesively bonded joints do unfortunately all too often not meet the requirements placed on them, resulting in failure during service life. In almost all engineering disciplines, codes and standards effectively regulate the design process. What are the reasons behind the noteworthy singularity of adhesive bonding? Both composites as a materials, and adhesive bonding as a joining technique have been widely investigated at several, if not almost all, levels of complexity. Yet this accumulated knowledge has not diffused into useful codes and standards to safely dimension adhesively bonded joints for composite materials. It is posited that this dichotomy between available and implemented knowledge is mainly due to three reasons: lack of specific qualification of designers regarding the new technology and the sheer extension of specific knowledge required; the attempt to clone "traditional" codes and standard where uniform approaches are sought after; the lack of specification regarding structural verification procedures. These issues have been recognised in other industries, e.g. railway and automotive, and more general solutions were offered that did not mimic traditional forms of coding, but consider adhesive bonding as a process, and not merely a joint. This paper aims at consider a much broader approach to coding, and offers ways out of the current misery of adhesively bonded joints for composite materials in civil engineering.

Keywords: adhesive, bonding, joints, structural, code, standard.

1362 - Shear Force in Bolted Connection due to Traffic and Temperature Loads in Hybrid Steel-FRP Bridges

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Abstract: As many bridges are reaching the end of their service life, researchers are searching for new solutions to extend the lifespan of those bridges. Fibre reinforce polymers (FRP) could be possible a solution for bridges with deck problems. Lightweight FRP decks can be installed quickly via bolted connectors on steel substructure. In general, shear force in the connector is not taken into account during the design of FRP decks because slip behaviour and interaction with steel substructure is unknown. This research connects to research at TU Delft on non-slip shear connectors for FRP decks. Aim of this paper is to quantify shear forces in bolted connectors due to traffic and temperature loads. The direction of webs, fibres in panel facings and the expansion coefficient of resin has been investigated to determine the influence of the FRP deck on the shear force in the connectors. To investigate the results of traffic loading and temperature loading on real bridges, a database of bridges in the Netherlands has been used. Results from the analyses offer an indication of the influence of the laminates on the shear force in the connectors and show shear force ranges that can occur in existing bridges.

Keywords: FRP, connectors, shear force, traffic load, temperature load.

1387 - Mechanical Properties of FRP Materials at Elevated Temperature. Definition of a Temperature Conversion Factor for Design in Service Conditions

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Abstract: One of the main concerns about the use of fibre reinforced polymer (FRP) materials in civil engineering structural applications is the potential reduction of their stiffness- and strength-related properties when exposed to elevated temperature. The first part of this paper presents an assessment of existing design guidelines for FRP structures, regarding the recommendations they provide about the reduction of FRP mechanical properties at elevated temperature. The second part of this paper presents a survey of test data available in the literature concerning mechanical tests at elevated temperature in FRP materials produced with different fibres, resins, shapes and manufacturing methods. The results of the survey show that the provisions available in existing design guidelines are not always accurate; moreover, in some cases, they are even non-conservative. Based on this assessment, the third part of the paper presents a method to define a temperature conversion factor for design purposes, consistent with the partial factor method of the Eurocodes, which was calibrated with the results included in the database. The method proposed takes into account not only the maximum service temperature experienced by the FRP material, but also its glass transition temperature; the method considers also the type of mechanical property, namely if it is either fibre- or matrix-dominated. The conversion factors obtained applying the method proposed presented a good agreement with the test data available in the literature.

Keywords: FRP materials, mechanical properties, temperature, design, conversion factor.

1393 - Influence of the Manufacturing Process on the Tensile Stress-Strain Response of Hybrid Glass/Carbon a nd Carbon/Carbon Composites

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Abstract: Despite the numerous advantages of fibre reinforced polymers (FRP) composites, ductility is still a major problem of these materials. Usual FRP composites are stiff and strong with little or no warning before final failure. The mentioned drawback can be mitigated using unidirectional (UD) hybrid composites (i.e. composites in which two or more different reinforcing materials are combined in the same polymeric matrix). In these materials the development of tensile pseudo-ductile behaviour during the failure process can be achieved. The amount of resin used to manufacture hybrid FRP composites is responsible for significant changes at their tensile stress-strain curve. It is believed that these changes are dependent on the interlaminar fracture toughness of the interface between layers. In the present work, the effect manufacturing methods on the tensile properties of hybrid composites was studied. Hand lay-up and vacuum bagging techniques were compared. Three combinations of dry unidirectional fabric materials were used to produce hybrid FRP composites, namely: i) high-modulus carbon, ii) standard carbon, and iii) E-glass. An epoxy-based resin was used as matrix. Failure modes, tensile elastic modulus, strength, and stress-strain curve were analysed. Finally, experimental results were analytically simulated.

Keywords: Hybrid Composite, Hand Lay-up, Vacuum Bagging, Analytical Analysis.

1394 - Cyclic Behaviour of Unidirectional Hybrid Interlayer Glass/Carbon and Carbon/Carbon Composites

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Abstract: The lack of ductility is a major drawback of fibre reinforced polymer (FRP) materials. As it is known, these materials are stiff and strong, but brittle with little or no warning before final failure. In the last decades, some solutions have been proposed with the aim of having FRP materials with pseudo-ductile behaviour. For instance, the use of unidirectional (UD) hybrid FRP materials (i.e. composites in which two different reinforcing materials are combined in the same polymeric matrix) can lead to tensile pseudo-ductile failure development. This is characterized by fragmentation of the low strain (LS) material and dispersed delamination of the LS material fragments from the undamaged high strain material. This concept is relatively new in the composites field, and almost unexplored in civil engineering applications. Nowadays, despite the research carried out in this area, the cyclic behaviour of pseudo-ductile UD hybrid composites is a remaining open question.
The main goal of the present work is to give new insights on the tensile-tensile cyclic behaviour of two pseudo-ductile UD hybrid composite systems, one comprising glass and high modulus carbon fibres and the other comprising standard-modulus carbon and high modulus carbon fibres. The behaviour under quasi-static and cyclic loading is investigated and the results are compared. Digital image correlation is used to observe damage evolution. The experimental program is described and the main results are presented and analysed.

Keywords: Composites, hybrid, cyclic, fragmentation, delamination

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1433 - Design Approach for FRP Structures: A Focus on Thermal Design

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Abstract: The adoption of FRP materials for the construction of new bridges has become a challenge to traditional bridge engineers who need to become familiar with the materials itself but also with the code to design efficient FRP structures. Today, there is various available FRP design guidelines all around the world and in Europe, thus, the CEN/TC 250 showed the willingness to merge these different documents into a new Eurocode standard.
The presented paper analyses the design approaches of the CEN Technical Report for FRP structures detailing the design of a pedestrian FRP bridge. This real footbridge was built in 2015, in France, by Janson Bridging Company (see Figure 1).
It consists of a two-span bridge for a total length of 36 m and a width of 2,4 m. The bridge consists of a sandwich structure with two GFRP (glass fibre-reinforced polymer) skins at the top and bottom of the bridge and a GFRP-reinforced foam core. The bridge was designed in compliance with the CUR96 recommendations, which follows the limit state design procedure and which involves reduction factors depending on the exposure conditions. The aim of the exercice is to compare the different design approaches and highlight the most important aspects. Here a focus is made on the thermal design. The results show that the method proposed in this paper can be further used for studies on the temperature behaviour of other general FRP bridges and to supplement the background document of the TS.

Figure 1. Pedestrian FRP Bridge, Saint-André de Cubzac, France, ©Photo P. Charbonneau.

Keywords: Eurocode, codes, standards and design guidelines, design analysis.

1461 - Flexural Behaviour of Hybrid FRC-GFRP/PUR Sandwich Panels

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Abstract: The present work has been developed in the scope of the research project "Easyfloor – Development of composite sandwich panels for building floor rehabilitation". This project aims at developing a hybrid sandwich panel, constituting an alternative construction system to conventional floor solutions, mainly for buildings rehabilitation. The developed hybrid sandwich panel is composed of a top face layer of steel fibre reinforced self-compacting concrete (FRC), a core of polyurethane (PUR) closed-cell foam and a bottom face sheet and lateral webs of glass fibre reinforced polymer (GFRP). The composite (GFRP/PUR) is manufactured by pultrusion, and its cross-section includes a sheet of GFRP between the FRC and PUR. After the production of the composite part, fresh FRC is poured onto the FRP component to materialize the top face of the panel.

Full-scale tests on the developed sandwich panels have been carried out to characterize their flexural behaviour. The experimental programme included flexural tests i) on single supported panels, ii) on two panels side adhesively bonded and iii) on single panels with different connection solutions to the walls.

The present work includes a detailed description of the developed panels and of the experimental programme. It also presents and discusses the relevant results. The observed performance of the tested specimens is critically analysed.

Keywords: Sandwich panels, composites, GFRP, PUR, fibre reinforced concrete.

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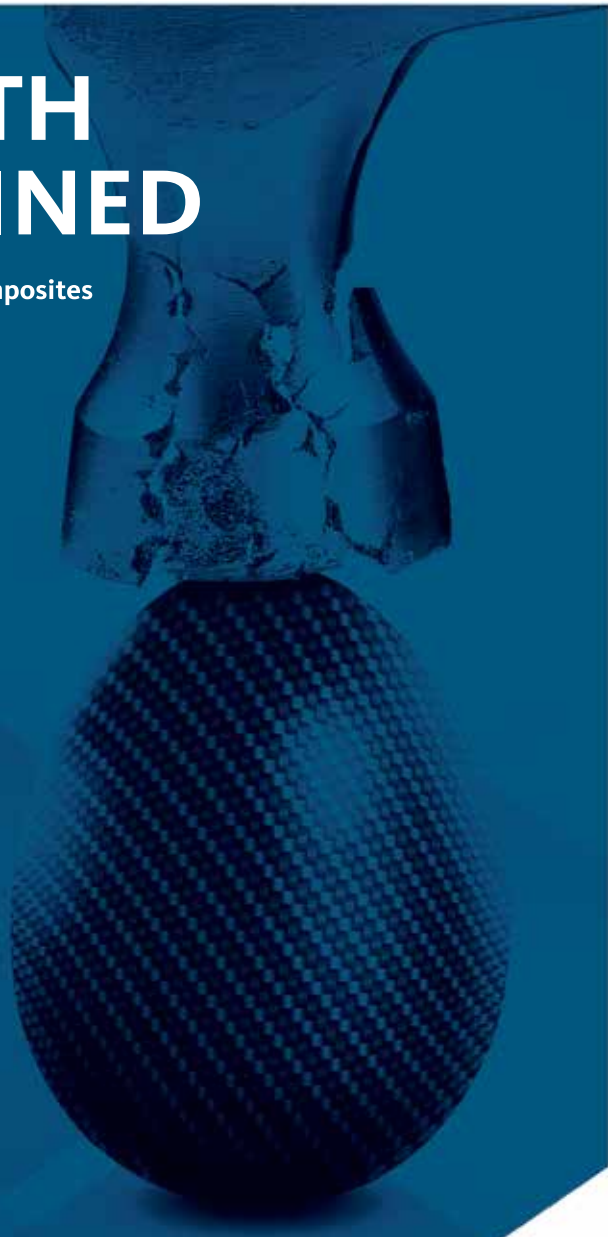

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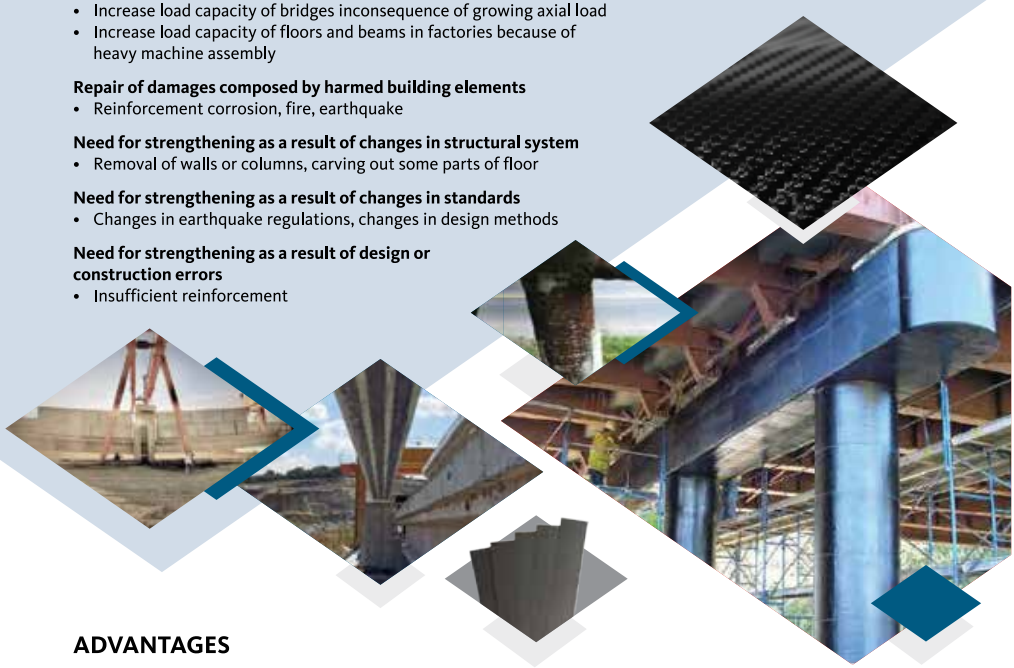

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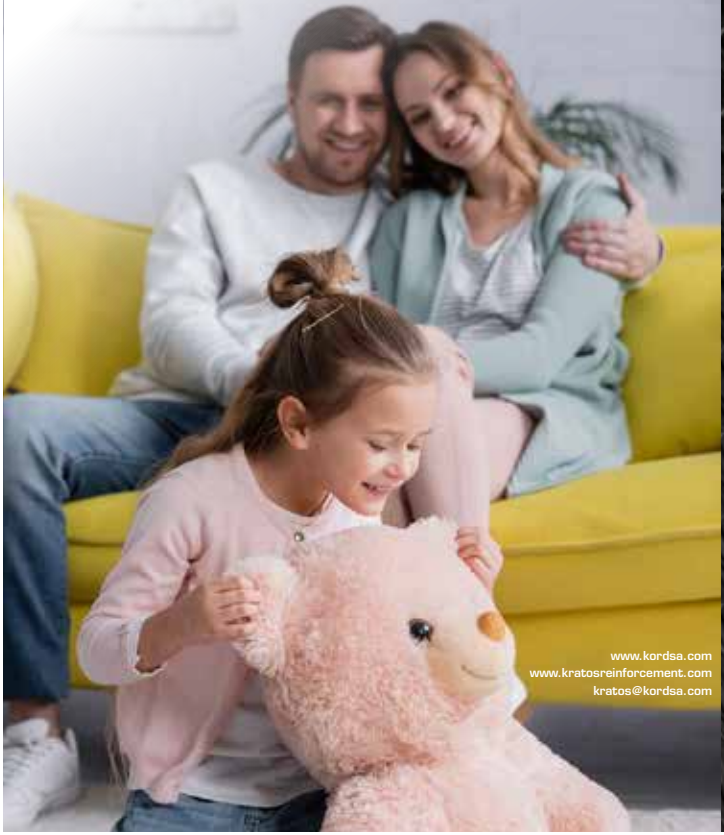

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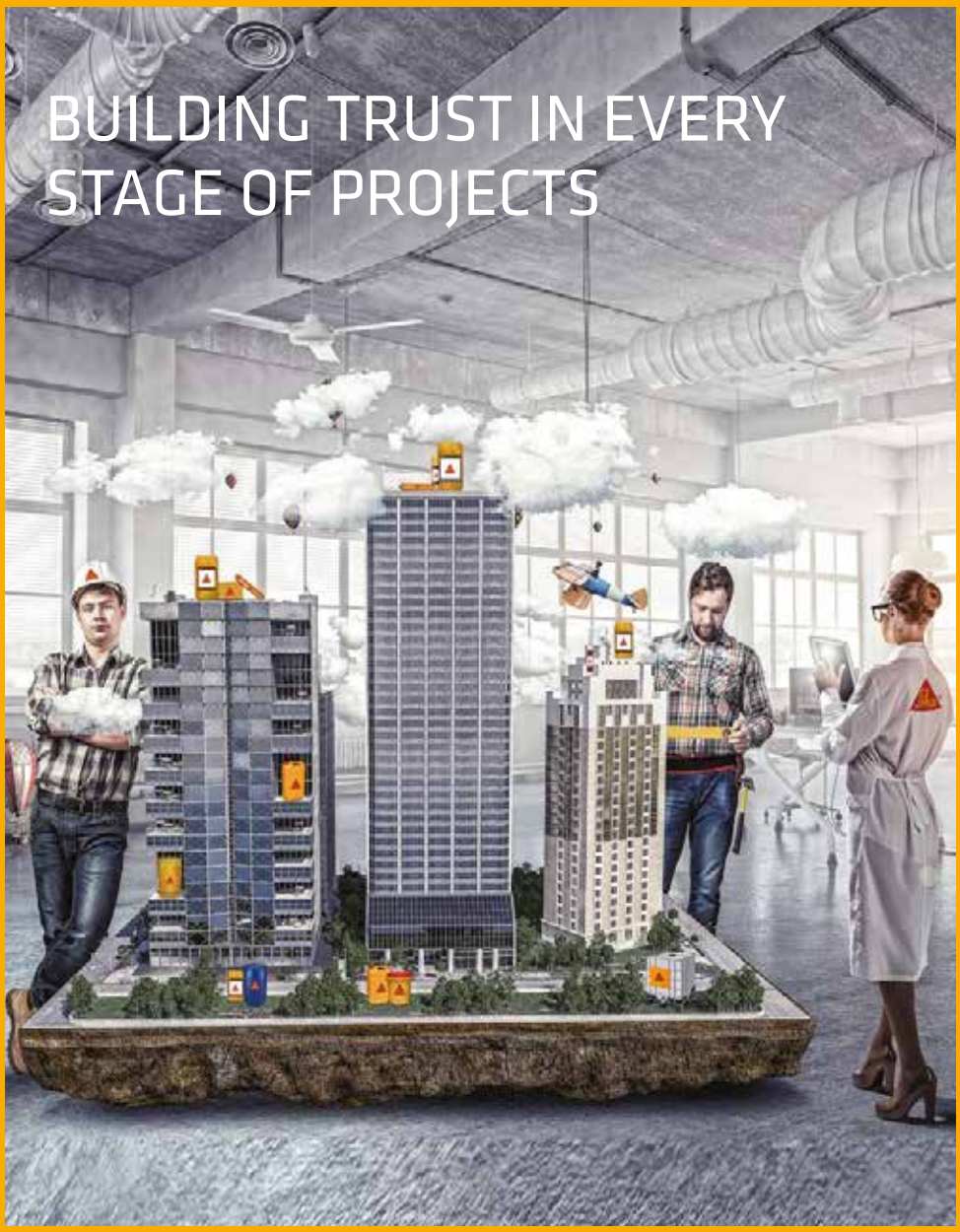

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