Performance Evaluation of Precast Concrete Block Reinforced with GFRP Rebars for Erosion Control

Y. Kim
Department of Civil & Environmental Engineering, Hanyang University, Korea

J. Sim
Department of Civil & Environmental Engineering, Hanyang University, Korea

C. Park
Department of Civil Engineering, Kangwon National University, Korea

A. Hanif
Department of Civil & Environmental Engineering, Hanyang University, Korea

ABSTRACT

Korea has four distinct seasons and the stream flow varies considerably as per the season. When the rain fills up the streams, the high speed flowing water slowly sloughs away the earth at the base of the slopes, thereby resulting in slope failure. Therefore, to prevent this scouring action, concrete blocks have been widely used for slope protection. But, as concrete block are exposed to water and humid environment, the steel rebars are more prone to corrosion. So the performance of these blocks happens to be less than expected. In this study, conventional steel rebars were replaced with GFRP rebars to solve the aforementioned problem. For performance evaluation of the concrete blocks, GFRP bar diameter and reinforcement ratio were kept the same as for steel reinforcing bars. After steam and atmospheric curing, these blocks were tested under various loading conditions. Consequently, the mechanical properties of concrete blocks reinforced with GFRP rebars were found better than those reinforced with steel bars.

KEYWORD

GFRP rebars, Precast concrete, Concrete blocks, Mechanical properties, Concrete erosion
Debonding Failures in CFRP-Strengthened Steel Structures

J.G. Teng
Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, China

D. Fernando
Department of Structural, Environmental and Geomatic Engineering, ETH Zürich, Switzerland

T. Yu
Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, China

X.L. Zhao
Department of Civil Engineering, Monash University, Melbourne, Australia

ABSTRACT

Strengthening of steel structures by bonding carbon fiber reinforced polymer (CFRP) plates (or laminates) has attracted much recent research attention. Debonding of the CFRP plate from the steel substrate is one of the main failure modes of CFRP-strengthened steel structures. This paper presents a summary of recent research conducted at The Hong Kong Polytechnic University (PolyU) aimed at the development of a good understanding of the mechanisms of and reliable theoretical models for debonding failures in CFRP-strengthened steel structures. Topics covered by this paper include steel surface preparation for reliable adhesive bonding, bond behavior between CFRP and steel, and finite element modeling of debonding failures in CFRP-strengthened steel beams and CFRP-strengthened rectangular steel tubes subjected to an end bearing load.

KEYWORDS

FRP, steel, strengthening, bond behavior, debonding.
Damage of Bridges by the Tsunami and Current Activity of JSCE Committee on Bridge Design against Tsunami

Kyuichi Maruyama
Prof., Department of Civil and Environmental Engineering,
Nagaoka University of Technology, Nagaoka, Japan

ABSTRACT

On March 11, 2011 the eastern Japan was hit by the largest earthquake in the history and the consequent tsunami caused awful disaster on human lives, assets and infrastructures. This paper describes mainly the damage of bridge structures by the tsunami. Estimated tsunami height was from 5 to 15 m in respective coastal area. The power of the tsunami was large enough to wash away concrete bridge girders. Most concrete girders were fallen down overturned near piers. Steel girders were washed away 300 to 500 m toward upstream from piers because of light weight. Totally more than 200 bridges were washed away, but the number is about 10 % of bridges in inundation area. Apparently short spanned and low rise bridges were survived. JSCE has established a research committee to investigate the tsunami force acted on bridge structures. In two years some results will be published.

KEYWORD

tsunami, earthquake, damage, bridge structures, JSCE committee
Proposals of CF, GF and NF Composites to Civil and Architectural Structures

Goichi Ben
Prof., Department of Mechanical Engineering, College of Industrial Technology
Nihon University, Chiba, Japan

ABSTRACT

Among various kinds of methods for fabricating fiber reinforced plastics (FRPs), a pultrusion method is a suitable method to fabricate FRP construction members because this method can fabricate the FRP members having a higher strength, stiffness and a uniform cross section with an arbitrary length. At first, this paper describes a new technique to mold not only phenolic foam composite but also a sandwich beam in which the phenolic foam composite as a core and a thin phenolic FRP layer as a faceplate are used. After the compressive strength and elastic modulus under high temperatures are examined and their results are compared with those under a room temperature, it is shown that the compressive properties of the phenolic foam composite and the sandwich beam are stable under higher temperatures. Next, a reinforcement method for the aged concrete is demonstrated by using the high performance CFRP strips fabricated with the pultrusion method. Three kinds of concrete beams reinforced with the CFRP strips with different vertical insert positions and different numbers of the CFRP strips are tested by a four point bending test method. In order to clarify the effects of CFRP strips, a concrete beam without reinforcement is also tested. The results of the experiment shows that the maximum deflections of the concrete beams reinforced with the CFRP strip are more than one hundred times larger compared with that of the concrete beams without reinforcement. Finally, a pultrusion technique is developed for fabricating green composites composed of PLA (Poly Lactic Acid) or PBS (Poly Butylene Succinate) resin as matrix and kenaf fibers as reinforcement. Their tensile strengths under the different temperatures are examined. These results are compared with those fabricated with a hot press molding. As a result, the performance of pultrusion method which can continuously fabricate green composites is demonstrated here.

KEYWORD

Carbon fiber, Glass fiber, Natural fiber, Pultrusion, Phenolic resin, Biodegradables resin
All FRP and FRP-Concrete Hybrid Components for Bridges: Experiments, Theories and Case Study

Peng Feng
Associate Prof., Department of Civil Engineering, Tsinghua University, Beijing, China

ABSTRACT

The experimental and theoretical research on FRP bridge is being conducted at Tsinghua University which aims at innovating high-performance FRP components and solving the emerging problems of FRP bridges. Three typical components, Outside Filament-wound Reinforced (OFR) FRP deck, Optimized Corrugate-skin Sandwich (OCS) FRP deck, and FRP-concrete hybrid beam are presented. The innovative configuration of OFR layer restricting the failure modes of delamination, in-plane shear failure, and debonding makes FRP more efficient used. The OCS FRP decks are optimized for moving load in simple supported condition as so to obtain the ultra-light FRP. Different hybrid beams using the pultruded FRP profiles are studied by experimental tests and theoretical analysis. The shear effect in hybrid beam is explained. Then, overall comments about FRP bridge components design are summarized. Based on the research of Tsinghua, four FRP pedestrian bridges are designed, including one cable-stayed bridge, one arch bridge, one girder bridge, and one suspending bridge. Three of them have been completed. The configurations and the structural behaviors of them are explained and summarized. This paper mainly discusses the rationale and advantages of FRP for bridges by different FRP components and application cases. These studies form part of a major on-going research programme at Tsinghua University.

KEYWORD

bridge deck, sandwich panel, shear connector, FRP-concrete hybrid beam, pedestrian bridge
Research and Development of Fibre Composites in Civil Infrastructure
- The Australian Experience

Thiru Aravinthan
Assoc. Prof., Centre of Excellence in Engineered Fibre Composites, University of Southern Queensland, Toowoomba, Australia

ABSTRACT

During the past 15 years, there have been considerable activities in the research and development of fibre composites (FC) in the Australian construction industry. Areas of activity have included bridge systems, replacement of hardwood girders, marine structures and strengthening of existing structures. The Centre of Excellence in Engineered Fibre Composites (CEEFC), a Research Centre at the University of Southern Queensland (USQ) has played a leading role in these developments. This work has involved not only the initial concept development but also the construction and deployment of full-scale prototypes. Through close involvement of major asset owners including state road and rail authorities and city councils, these technologies have evolved from initial technology demonstrators to become viable commercial alternatives to traditional structural solutions. This paper highlights some of the past and present research and development (R&D) projects on engineered fibre composites that the authors have been involved in. These projects include the development of the Australia’s first fibre composite bridge, innovative strengthening systems using fibre composites, fibre composite railway sleepers, a fibre composite windmill structure and other innovative applications of engineered fibre composites in civil infrastructure. Future R&D prospects on this advanced composite material are also discussed.

KEYWORD

fibre composites, research and development, bridges, structural rehabilitation
Comparison of Different Configurations for FRP Strengthening of Masonry Walls

A. Sayari
Faculty of Engineering, Islamic Azad University, Sanandaj Branch, Iran

T. Donchev
School of Civil Engineering and Construction, Kingston University, London, UK

ABSTRACT

Masonry buildings form significant part of the cultural heritage in the world. One of most important aspects of safety of old and historical buildings is the vulnerability to lateral loads such as earthquake and wind loads and the need to appropriate strengthening. Fiber reinforced polymer (FRP) composite materials are recently developed option for strengthening of masonry buildings. The application of FRP composites as externally bonded reinforcement in repairing and strengthening the masonry walls has becoming more attractive than the traditional methods which are based on steel elements. Their excellent strength-to-weight ratio, easy installation and minimized damage for the existing structure made them the best option for strengthening of listed buildings and structures. In this research, several finite element analytical models are developed to predict the response of masonry walls in case of out-of-plane loading. The behavior of FRP strengthened masonry walls is examined and then compared with the published results in this subject area. The wall panels made of clay bricks have been investigated and the effectiveness of different types and various amounts of FRP elements used for strengthening is analyzed.

KEYWORD

Masonry, FRP, Out-of-plane, Modeling, Strengthening
Experimental Study on Strengthening Effect of CFRP Strand Sheet on RC Beams Applied with Several Kinds of Adhesives

Atsuya. Komori. And Kenshi. Taniguchi
Infrastructural Use Div., Nippon steel materials Co., Ltd , Tokyo, Japan

Satoru. Nakamura
Civil engineering Sales Div., Sato-Benec Co., Ltd , Oita, Japan

Kouhei Yamaguchi. And Shinichi Hino
Department of Civil Engineering, Kyusyu University, Fukuoka, Japan

ABSTRACT

When attaching continuous fiber sheets on concrete members on site, bonding defection such as bubbles or mal-impregnated area of the continuous fiber sheets sometimes happens. FRP (Fiber Reinforced Polymer) strip bonding method doesn’t have this kind of problem because it is impregnated and cured at the factory, but it also has demerit of less adhesion property caused by small bonding area. To solve these problems, we have developed advanced FRP strand sheets which consist of bunch of individually hardened continuous fiber thin strands aliened and composed uni-directionally. The FRP strand sheets can be easily attached on the surface of concrete members with putty like adhesive and no impregnation needed. Thus, the advanced strand sheet method can assure better construction quality and cut down the application time and costs. The purpose of this study is to clarify the influence of the differences of the adhesives on strengthening effect of strengthened RC (Reinforced Concrete) beams with FRP strand sheets. In this study, adhesives of Epoxy, MMA (Methyl methacrylate) resin, PCM (Polymer Cement Mortar) and JCM (Ultra rapid hardening Jet cement mortar) were tested and compared. As results, it is found that all adhesives were effective for improving flexural capacity of RC beams and the bonding strength was depend on the kind of adhesives.

KEYWORD

CFRP, FRP, Strand-sheet, RC-beam, Epoxy, PCM, MMA, Ultra rapid hardening-cement, Mortar, Flexural strength, CFS, CFSS,
Efficiency and Critical Points of Strengthening Masonry Structures with FRP

Jiri Witzany
Prof., Department of Building Structures, CTU in Prague, Czech Republic

Tomas Cejka
Lecturer, Department of Building Structures, CTU in Prague, Czech Republic

Radek Zigler
Lecturer, Department of Building Structures, CTU in Prague, Czech Republic

ABSTRACT

This paper presents the results of theoretical and experimental research focused on the explanation of the problems related to dramatic differences in the deformation characteristics of FRP fabrics and brick masonry. It investigates the mutual interaction of masonry possessing a relatively lower modulus of deformation $E_d$ and a strengthening FRP layer with a relatively high modulus of elasticity $E_{CFRP}$ ($E_{CFRP}$ to $E_d$ ratio $\approx 50;70$), the problems of the interaction of strengthening FRP layers with masonry in areas exposed to pressure (FRP buckling) and the problems related to efficient exploitation of mechanical characteristics of FRP with regard to specific mechanical characteristics of masonry.

Special attention within the experimental research is focused on the strengthening of masonry pillars exposed to the external environment and damaged by tensile cracks in the case of reconstructions of historic buildings jeopardized by further cumulative failures and on-going disintegration and the failure mechanism of masonry pillars under low-cycle alternating load.

The paper was written with support from Research Plan MSM 6840770001 “Reliability, optimization and durability of building materials and structures”.

KEYWORD

carbon fiber, masonry, experimental research, strengthening
Shear Strengthening of RC Beams
using FRP Mesh and PVA Short Fiber Mixed Shotcrete

Takuro Nakamura and Fumio Taguchi
Civil Engineering Research Institute for Cold Region, Sapporo, Japan

Yusuke Kurihashi and Norimitsu Kishi
Muroran Institute of Technology, Muroran, Japan

Hiroshi Mikami
Sumitomo Mitsui Construction Co., Ltd., Nagareyama, Japan

ABSTRACT

Fiber Reinforced Polymer (FRP) is currently used worldwide to repair and/or strengthen infrastructures such as bridges and buildings. This paper presents results of an experimental investigation on the shear load-carrying capacity of reinforced concrete (RC) beams which were strengthened using FRP mesh and shotcrete. The strengthening materials were polyvinyl alcohol short fiber mixed shotcrete (PVA shotcrete) and Aramid FRP mesh (AFRPm) or Carbon FRP mesh (CFRPm). This investigation was carried out on the basis of the experimental results for four RC beams without stirrups: a plain RC beam as a reference beam; a RC beam strengthened with PVA shotcrete; a RC beam strengthened with both AFRPm and PVA shotcrete; and a RC beam strengthened with both CFRPm and PVA shotcrete. These strengthening materials were applied to side and bottom surfaces of these beams. The beams were statically surcharged under four-point load conditions. From these experimental results, it is seen that RC beams can be significantly upgraded by applying the proposed method. Furthermore, an increment of the shear load-carrying capacity for these RC beams can be evaluated by using the design formulae developed for RC beams with ultra-high strength fiber reinforced concrete and jacketed with FRP sheet.

KEYWORD

Shear strengthening method, AFRP mesh, CFRP mesh, PVA short fiber, Shotcrete
Fibre Composites for High Pressure Pipeline Repairs, in-air and subsea – An Overview

Md Shamsuddoha, Md Mainul Islam, Thiru Aravinthan, Allan Manalo, Kin-tak Lau

Centre of Excellence in Engineered Fibre Composites (CEEFC), Faculty of Engineering and Surveying, University of Southern Queensland, Toowoomba, Australia

David Elder

CRC for Advanced Composite Structures Australia, Melbourne, Australia

ABSTRACT

In 2001 it was reported that in North America alone, corrosion to the Oil & Gas pipeline distribution network costed approximately $2-3.3 billion per annum with 10% of that cost being associated with actual failure of the pipeline. In addition pipelines are also susceptible to erosion and mechanical damage producing further losses in pipe structural integrity. This results in high maintenance costs, possibility of adverse environmental consequences and the costly interruption to product transportation and distribution. The cost and technical challenges of adequately addressing repair are significant and greatly increase for underwater applications particularly with increasing water depth. It therefore induces the need of searching for alternative repair techniques involving new advanced materials for ease of installation and application against adverse environmental effects in the long run. Fibre composite materials provide excellent advantages over conventional metals in engineering practices for many decades. These advantages make fibre composite suitable candidate for effective repair technology. This paper provides a comprehensive review on the recent development and future prospect of using these materials for in-air and underwater pipeline external repairs. Various aspects of technical knowhow; benefits and shortcomings of the repair considerations are also presented.

KEYWORDS

Composite, pipeline, underwater, repair.
Shear Deformation of RC Beams Jacketed with Large Fracture Strain FRP in the Post-yielding Region

Tidarut Jirawattanasomkul
Ph.D. Candidate, Department of Civil Engineering, Hokkaido University, Sapporo, Japan

Naruse Ryota
Master's student, Department of Civil Engineering, Hokkaido University, Sapporo, Japan

Dawei Zhang
Post doctoral fellow, Department of Civil Engineering, Hokkaido University, Sapporo, Japan

Tamon Ueda
Prof., Department of Civil Engineering, Hokkaido University, Sapporo, Japan

ABSTRACT

The strengthening of the existing reinforced concrete (RC) members with a large fracture strain FRP has been successfully developed in order to enhance the shear strength and ductility of members under serious seismic forces. Although the models for predicting deformation have existed in many specifications, the design methods have not clarified the shear deformation precisely. In post shear cracking region, the experimental results indicate that the shear deformation mechanism significantly increases up to the failure of the member. Therefore, the deformation components are investigated in the plastic hinge region of RC beams with and without FRP jacketing. Based on the truss analogy, the method to predict the shear deformation is suggested at the post-yielding and at high ductility levels. In the model, the method of estimating the shear deformation takes into account the yielding of reinforcement and the reduction of compression strut angle due to the development of shear crack. To verify the application of the proposed model, measurements of Linear Variable Differential Transformers (LVDTs) and the Image analysis are evaluated for the tested beams in the critical plastic hinge region. Conclusions are drawn regarding the total deformation separating into the flexural and shear deformation components at each displacement level. Diagrams resulting from the proposed shear deformation model are also presented, indicating that the shear deformation mechanism becomes critical for beams with a short span to depth ratio.

KEYWORD

PET, shear deformation, Image analysis, truss model
Mechanical Behavior of Plate Bonded FRP Sheets
Under Uniaxial Compression Load

Yusuke Okuyama
Ph.D. student, Nagaoka University of Technology, Civil and Environmental Engineering, JAPAN

Takeshi Miyashita
Specially appointed associate professor, Nagaoka University of Technology, Civil and Environmental Engineering, JAPAN

Tatsuo Ogata
Nippon Expressway Research Institute Co., Ltd.

Kazuo Fujino
Nippon Expressway Research Institute Co., Ltd.

Kazuo Ohgaki
Kawasaki Heavy Industries, Ltd.

Yuya Hidekuma
Nippon Steel Composite Co., Ltd.

Wataru Horimoto
Kurabo Industries, Ltd.

Masatsugu Nagai
Professor, Nagaoka University of Technology, Civil and Environmental Engineering, JAPAN

ABSTRACT

This paper describes a fundamental study on the rational repair and reinforcement of webs in corroded steel girder bridges achieved using fiber reinforced plastic (FRP). A uniaxial compression test of steel plates bonded by various FRP sheets was carried out. The objective of this test was to select FRP sheets having a reinforcing effect on the steel plate following large deformation induced by buckling. Furthermore, a layer of polyurea putty was inserted between the steel plate and the FRP sheet and its effect was investigated. Finally, a method that predicts the elastic buckling load of the steel plate with FRP sheets was developed.

KEYWORDS

Fiber reinforced plastic, steel plate, uniaxial compression test, buckling
Stress Analysis for Steel Plate Multilayered CFRP under Uniaxial Loading

Takeshi Miyashita
Specially appointed Assoc. Prof., Department of Civil and Environmental Eng., Nagaoka University of Technology, Nagaoka, Japan

Masatsugu Nagai
Prof., Department of Civil and Environmental Eng., Nagaoka University of Technology, Nagaoka, Japan

ABSTRACT

A steel plate layered with more than two carbon-fiber-reinforced polymers (CFRPs) has not yet been theoretically analyzed. Since the order of differential equations of the stress of the plate layered with $n$ CFRPs is $2n$, the equation gets complicated with increasing number of CFRPs. Finite element analysis is usually employed for analyzing steel plates layered with more than two CFRPs. However, since the adhesive layers between CFRPs are extremely thin, very fine meshing is required. Therefore, the objective of this study was to develop a new stress analysis method for a steel plate with multilayered CFRPs under uniaxial loading. The strains in each layer were considered state variables in the first-order simultaneous differential equations derived from force equilibriums in infinitesimal regions. A general solution for strain was numerically calculated by the eigenvalue analysis of a system matrix formulated from the differential equations. Unknown coefficients in the general solution were determined from continuous and boundary conditions for strains in each layer. The proposed method was validated by a comparison with analytical solutions, a laboratory experiment, and finite element analysis. The comparison confirmed that the proposed method included conventional analytical solutions and facilitated analysis of stress distributions on a steel plate with multilayered CFRPs.

KEYWORDS

CFRP, steel plate, uniaxial loading, stress analysis, differential equations
Experimental Study of the Bond Strength between Steel Substrate and CFRP under Impact Tensile Loads

H. Al-Zubaidy, X.L. Zhao*
Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia
R. Al-Mahaidi
Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, Hawthorn, VIC 3122, Australia

ABSTRACT

Carbon fibre reinforced polymer (CFRP) has attracted a great deal of attention for upgrading and/or rehabilitating steel structures following its successful application for the strengthening of concrete structures. It is vital to maintain a sound bond between the CFRP and the steel substrate during service by selecting appropriate adhesives. The effect of dynamic loading (e.g. impact) on such bond is not well understood. This paper describes an experimental investigation of the efficiency of the bond between steel and normal modulus CFRP sheets under dynamic tensile loads of various loading speeds. The pull-off adhesion testing method was adopted. It was found that significant enhancement in adhesion bond strength for two types of resins was achieved at high strain rates. The failure mechanisms of both adhesives were remarkably influenced by speeds of loading and they illustrated noticeable changes compared to static loads.

KEYWORD

Adhesive adhesion strength, CFRP sheet, steel plate, dynamic tensile loads, pull-off test
Experimental Study on Debonding Behavior of CFRP for Axial Tensile Reinforced Steel Plate by CFRP Strand Sheets

Yuya Hidekuma
Infrastructure Use Division, Nippon Steel Materials Co., Ltd, Composites Company, Tokyo, Japan

Akira Kobayashi
Infrastructure Use Division, Nippon Steel Materials Co., Ltd, Composites Company, Tokyo, Japan

Yusuke Okuyama
Department of Civil and Environmental Engineering Nagaoka University of Technology, Niigata, Japan

Takeshi Miyashita
Specially Appointed Associate Professor, Top Runner Incubation Center for Academia-Industry Fusion, Nagaoka University of Technology, Niigata, Japan

Masatsugu Nagai
Prof., Department of Civil and Environmental Engineering, Nagaoka University of Technology, Niigata, Japan

ABSTRACT

Steel members are often corroded by various mechanisms, and their performance decreases dramatically due to corrosion. As a repairing method for corroded steel members, the CFRP (Carbon Fiber Reinforcement Polymer) bonding methods with resin to the steel member were developed. These methods are known as an efficient and economical method for repairing because no heavy equipment is necessary at work site. In recent years, the CFRP strand sheet which consists of bunch of individually hardened continuous fiber strands was developed. The purpose of this study is to propose the repairing method for steel members by using the CFRP strand sheets. In order to clarify the effect of number of ply, type, width of CFRP and length of step on debonding property of CFRP, the tensile tests of steel plate which reinforced by the CFRP strand sheets were performed. As a result, it was clarified that the each parameters affect debonding property of CFRP reinforcement. The results proposed the optimal bonding method of CFRP strand sheets to steel members.

KEYWORD

steel strength, corrosion, tensile test, CFRP strand sheet, debonding, interfacial shear stress
FRP-to-Metal Bonds:  
Effect of Test Specimen Configuration on Interfacial Stresses

J.Q. Yang  
PhD Candidate, Department of Civil Engineering, The University of Hong Kong, P.R. China

Scott T. Smith  
Associate Professor, Department of Civil Engineering, The University of Hong Kong, P.R. China

Peng Feng  
Associate Professor, Department of Civil Engineering, Tsinghua University, P.R. China

ABSTRACT

Metallic construction materials can be strengthened relatively easily and effectively with externally bonded fibre-reinforced polymer (FRP) composites and in order to understand the bonded interface, researchers have tested FRP-to-metal bonded joints. Despite several different joint configurations being employed to date, no systematic investigation has yet been conducted on the effect of different configurations. This paper presents the results of a finite element investigation on the interfacial stresses induced in different FRP-to-metal joint test configurations. The distributions of interfacial shear and normal stresses are determined for single-shear and double-shear joints in which either the metal or FRP is loaded and the relative differences and similarities are also established between the joints under investigation. A fictitious FRP-strengthened beam is then modelled and specific joint configurations which most accurately represent the interfacial stress distributions in the beam at selected locations are identified. The findings of this study will aid researchers in selecting FRP-to-metal joint configurations most appropriate for representing the interfacial stress states in different FRP-strengthened member scenarios.

KEYWORDS

Bond, Finite Element Modelling, FRP, Interfacial Stresses, Metal, Strengthening
Tensile and Compressive Test on Thickness-Reduced Steel Plate Repaired by CFRP Strand Sheet and Underwater Epoxy with Bond Defects

Yasuo Kitane
Assoc. Prof., Department of Civil Engineering, Nagoya University, Nagoya, Japan

Xiao Chen
Graduate Student, Department of Civil Engineering, Nagoya University, Nagoya, Japan

Yoshito Itoh
Professor, Department of Civil Engineering, Nagoya University, Nagoya, Japan

Toshiyuki Ishikawa
Assist. Prof., Department of Urban Management, Kyoto University, Kyoto, Japan

ABSTRACT

There are a significant number of marine steel structures suffering severe corrosion damage, and they are seriously in need of repair or strengthening to prevent structural failure. This study is focused on a repair technique using carbon fiber reinforced polymer (CFRP) sheet, especially, CFRP sheet bonding in the underwater environment. Underwater bonding of CFRP sheets is not yet a matured technique, and its repair performance for corroded steel structures is not fully understood. One of the issues is the effect of bond defects on the repair performance. Air bubbles are often found to be trapped in the adhesive layer. To examine an effect of bond defects on the repair performance, uniaxial loading tests are performed on thickness-reduced steel plates with CFRP strand sheets bonded by using underwater epoxy as adhesive. In total, sixteen CFRP strand sheet bonded steel plates are prepared, where test parameters are loading directions of tension and compression and the location of bond defects. The effect of bond defects on the repaired performance is examined in terms of yield strength, initial stiffness, and failure mode. As a result of experiment, it is found that two types of defects considered in this study do not affect repair performance significantly. However, when a CFRP bonded steel plate is under compression, buckling of CFRP strand sheet may control its compression strength, resulting in a smaller strength than the tensile strength.

KEYWORD

CFRP, steel plate, repair, bond defect, underwater
Capacity Development of Externally Bonded CFRP Subject to Oscillating Loads During Resin Cure

Kent A. Harries, Ph.D., FACI, P.Eng
Associate Professor, Civil and Environmental Engineering, University of Pittsburgh, USA

Wen-wei Wang, PhD
Associate Professor, Department of Bridge Engineering, Southeast University, Nanjing, China

Jian-Guo Dai, PhD
Assistant Professor, Civil & Structural Engineering, The Hong Kong Polytechnic University, Hong Kong

ABSTRACT

In many applications, particularly those associated with bridge structures, externally bonded FRP applications are installed and required to cure under conditions of transient live load, such as traffic traversing a bridge. This paper focuses on the behaviour of the bonded FRP during cure when subject to oscillating loads intended to mimic transient live load. Five CFRP-strengthened reinforced concrete beams were subject to loads oscillating at 1 Hz between 30% and 50% of their initial unstrengthened capacity for 48 hours immediately following CFRP installation. All beams were instrumented for CFRP, internal reinforcement and concrete strains and continuously monitored during the oscillatory loading regime. After 48 hours, each beam was tested monotonically to failure. This paper reports the results of the tests, focusing on the behaviour observed during the 48 hour cure/oscillatory load regime. Early in the curing cycle the resin transmits very little stress to the CFRP and behaves in a ‘visco-elastic’ manner. As cure progresses, the CFRP becomes effective as evidenced by increasing CFRP strains and decreasing internal reinforcement strains. Additionally, the CFRP behaviour transitions to an essentially elastic behaviour. This behaviour during cure has apparent implications on the eventual fully cured CFRP response including aspects of effective bond length and may affect creep-related behaviour of the CFRP and CFRP-to-concrete bondline.

KEYWORDS

CFRP cure, cyclic load, traffic load
FRP Anchorage Systems for Infill Masonry Structures

Dillon S. Lunn
Graduate Research Assistant, Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, North Carolina, USA

Sami H. Rizkalla
Distinguished Professor, Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, North Carolina, USA

Shohei Maeda
Formerly Graduate Research Assistant, Laboratory of Engineering for Maintenance System, Hokkaido University, Sapporo, Japan

Tamon Ueda
Professor, Laboratory of Engineering for Maintenance System, Hokkaido University, Sapporo, Japan

ABSTRACT

This paper summarizes the research program undertaken to examine the behavior of several innovative anchorage systems for Fiber-Reinforced Polymer (FRP) strengthening systems for infill masonry wall structures. The research includes an experimental program comprising twelve infill wall specimens. All specimens consisted of two reinforced concrete (RC) beams, simulating the supporting RC elements of a typical building, which were in-filled with solid brick masonry. The specimens were loaded out-of-plane using an airbag to apply uniformly distributed pressure to the masonry. Glass (GFRP), Carbon (CFRP), and a new type of FRP with high fracturing strain, PET (Polyethylene Terephthalate), were used to evaluate the performance of the various anchorage systems. The types of anchorage investigated in the study include overlap, steel plate, wrapping around an embedded CFRP bar, CFRP fiber anchors, CFRP shear keys, and a continuous near surface mounted (NSM) CFRP system. Experimental results indicate that the type of FRP anchorage had a significant effect on the failure mode, ductility, and load carrying capacity. Strengthening of the infill walls lead to a substantial increase in the load carrying capacity ranging from 1.6 to 7.2 times the capacity of the unstrengthened infill wall.

KEYWORD

Infill Masonry, FRP Anchorage, Out-of-Plane, PET, GFRP, CFRP
Partially Cured Epoxy Adhesive for Anchoring Prestressed CFRP Strips on Concrete

Julien Michels
Dr., Swiss Fed. Lab. for Materials Science and Techn. (Empa), Dübendorf, Switzerland

Christoph Czaderski
Senior Researcher, Swiss Fed. Lab. for Materials Science and Techn. (Empa), Dübendorf, Switzerland

Raafat El-Hacha
Professor, University of Calgary, Calgary, Canada

Masoud Motavalli
Lab. Head, Swiss Fed. Lab. for Materials Science and Techn. (Empa), Dübendorf, Switzerland
Assistant-Professor, University of Tehran, Tehran, Iran

ABSTRACT

Prestressed Carbon Fiber Reinforced Polymer (CFRP) strips are an efficient retrofitting technique for reinforced concrete structures. An adequate anchorage system is necessary in order to guarantee a satisfactory structural behavior. At Empa, a non-mechanical anchorage method based on a purely epoxy adhesive connection between strip and concrete has been developed. A key factor of the system is the ability of the epoxy to cure faster under high temperature. Repetitive local curing followed by a continuous prestress force release at the strip end will eventually lead to zero prestress force and thus prevent debonding failure. This paper presents an experimental investigation on several pull-off and prestress force releasing tests under different heating configurations. These tests describe the short-term anchorage resistances available for the prestress force release in the gradient anchorage after accelerated curing at high temperature. Comparisons with test specimens cured under room temperature for several days will be shown. It is demonstrated that under certain conditions partially cured epoxy can involve higher bearing capacity than fully cured epoxy, as the softer material behavior induces a better shear stress distribution over the bond length.

KEYWORDS

bond behavior, bond stress, epoxy adhesive, prestressed CFRP strips
The Study of FRP Sheet Effectiveness on Structural Behavioral of AAC Blocks

Asghar V. Oskouei
Department of Civil Engineering, Shahid Rajaee University, Tehran, Iran

Shahed Rasouli
Department of Civil Engineering, Shahid Rajaee University, Tehran, Iran

ABSTRACT

This article presents the experimental study on Autoclaved Aerated Concrete (AAC) specimens retrofitted by Fiber-reinforced polymer (FRP) sheets to improve the structural properties like compressive and tensile strength of elements that made of AAC. In this study, FRP sheets that are used to strengthen concrete structures are two types: Carbon and Glass. There are no sufficient studies for FRP application on AAC. Autoclaved Aerated Concrete is one such material that applied in recent years in the world. There is an interest in evaluating the feasibility of application of FRP to retrofit existing structures or elements made of AAC (e.g., beams, columns, etc.). The specimens used in this study include tensile specimens without FRP and with a scheme of FRP applied to the external surfaces for flexural specimens. The measured test data provide a basis for evaluating the accuracy of existing strength-design equations to predict the capacity of such specimens. Test results shows that the application of FRP at the bottom and top of the tensile specimens, increases the load and deflection capacities. Comparison of test results and calculated strengths shows that the existing guidelines such as ACI 440.2R and ACI 523.4R give safe estimates of flexural strength for AAC-FRP structural elements.

KEYWORD

Autoclaved Aerated Concrete (AAC), FRP, retrofitting, Reinforcing, Bending, tensile
Feasibility Study on Increasing Bending Stiffness of FRP Girders by Bonding CFRP Strips and Bonding Girder Sections

Onek Denis Obedi
Pacific Consultants, Co., LTD (PCKK), Tokyo, Japan

Shuhei Sugai, Hitoshi Nakamura and Ken-ichi Maeda
Department of Civil and Environmental Engineering, Tokyo Metropolitan University, Tokyo, Japan

Ken-ichi Yaginuma
East Japan Railway Company, Saitama, Japan

ABSTRACT

Substantial deflection of FRP composite girders when subjected to flexural loading is still a major design challenge that structural engineers are faced with. In this study, a way to increase the bending stiffness of FRP girder is suggested. This study investigated the feasibility of (a) externally bonding CFRP strips of high elastic modulus onto the flanges of FRP girder and (b) stacking one girder on another to form a large-scaled section girder as means of increasing the bending stiffness of FRP girders.

During the research, analytical and experimental studies were conducted to evaluate; the effectiveness of the adhesive layer in holding the CFRP strips to FRP girder and FRP girder to FRP girder, the applicable span length of a footbridge (proposed structure) constructed using FRP girders with CFRP strips bonded on its flanges and stacked girders, and the ultimate bending strength of the FRP composite girder.

It was noted that the bending stiffness of FRP girder can be effectively increased by externally bonding CFRP strips onto its flanges depending on the mechanical properties of the CFRP strips. By stacking one girder on another, the ultimate strength of the girder almost quadrupled as compared to a simple girder.

From this study, the conclusion is that; the adhesive layer effectively provided the bonding strength required to hold the constituent members together thus additional connectors like bolts and rivets are not necessary. The ultimate bending strength of FRP girders can be considerably increased by either using CFRP strips or bonding girder sections.

Therefore, strengthening FRP girder by bonding CFRP strips and bonding girder sections are feasible methods for increasing the bending stiffness of FRP girders and can be useful in the design of FRP footbridges.

KEYWORD

FRP footbridge, bending stiffness, bonding CFRP strip, bonding girder sections
Seismic Performance of Beam-Column Joints Reinforced With GFRP Headed Bars

Mohamed H. Hasaballa
PhD Candidate, Dept. of Civil Eng., University of Manitoba, Winnipeg, MB, Canada

Ehab F. El-Salakawy
Canada Research Chair Professor, Dept. of Civil Eng., University of Manitoba, Winnipeg, MB, Canada

ABSTRACT

Concrete beams, slabs and recently columns reinforced with Fibre-Reinforced Polymers (FRP) reinforcements have shown considerable deformability under monotonic and fatigue loading. The behaviour of FRP bars under tension-compression load reversals in reinforced concrete (RC) beam-column joints and frame structures has not been fully investigated yet. Furthermore, concerns still remain regarding the ability of FRP-RC frame structures to dissipate energy in seismic loading events due to the elastic-linear behaviour of the FRP reinforcement. This paper attempts to partially fulfill this gap by investigating the structural performance and ultimate capacity of concrete beam-column connections reinforced with glass FRP bars. Two full-scale exterior beam-column joint (T-shaped) prototypes were constructed and tested under simulated seismic load conditions. The main test parameter is the detailing of the beam longitudinal bars within the joint by using either straight-headed bars or bent bars. Test results are presented in terms of load-drift ratio and load-strains in longitudinal reinforcement relationships. The experimental results showed a superior performance for the straight-headed bars over the bent ones.

KEYWORD

Seismic performance, beam-column joints, GFRP headed bars, GFRP bent bars, drift ratio
Investigation on GFRP Bar Performance in High Strength Concrete Footing

Mohammad Pirgholi Kivi
Department of Engineering, Shahid Rajaee University, Tehran, Iran

Hassan Araghi
Department of Engineering, Azad University of South Tehran, Tehran, Iran

Asghar Vatani Oskouei
Department of Engineering, Shahid Rajaee University, Tehran, Iran

ABSTRACT

Usage of GFRP (Glass Fiber Reinforced Polymer) bars in construction is developing nowadays because of its unique properties among corrosion resistance, high tensile strength and ease of application and handling. Beside of its advantages however have some different structural behavior in compare to normal steel reinforcement in concrete members that necessary to light up accurately by appropriate test methods. One of these points is bond behavior of GFRP bars in Concrete. In this paper, structural behavior of concrete footing reinforced with GFRP bars laid on real condition, sand filled box, is studied by full scale test. Besides, bond behavior of this system focused by ACI recommended pullout test method and other properties of bars used in specimens also are tested. Upshots of study illuminate that high strength concrete allows GFRP bar to reach maximum bond strength along failure of bar surface. This bond behavior leads to appropriate behavior of footing and bars involvement in tension.

KEYWORD

GFRP bar, strain, bond strength, load-deflection, high strength concrete
Use of CFCC Tendons and Reinforcements in Concrete Structures for Durability

Tsuyoshi Enomoto
Manager, Total Cable Technology Division, Tokyo Rope Mfg., Tokyo, Japan

Kenichi Ushijima
Manager, Total Cable Technology Division, Tokyo Rope Mfg., Tokyo, Japan

ABSTRACT

This paper presents a brief description of the development, usage, and application of non-corrosive Carbon fiber composite cable (CFCC). In addition to that, case studies of the use of CFCC in bridges are discussed to share the technical information about the successful deployment and various applications of the CFCC tendons and reinforcements. CFCC has already been used as reinforcing materials for more than 140 structures. So far, it is a proven fact that durability of prestressed concrete bridge using CFCC tendons is more than 23 years through harsh environmental conditions, without any deterioration.

KEYWORD

carbon fiber reinforced polymer, durability, non-corroding, prestressed, precast concrete
Evaluation of a Shear Wall Reinforced with Glass FRP Bars Subjected to Lateral Cyclic Loading

Nayera Mohamed
PhD candidate, Department of Civil Engineering, University of Sherbrooke, Sherbrooke, Canada

Ahmed Sabry Farghaly
Post-Doctoral Fellow, Department of Civil Engineering, University of Sherbrooke, Sherbrooke, Canada

Brahim Benmokrane
Professor, Department of Civil Engineering, University of Sherbrooke, Sherbrooke, Canada

Kenneth W. Neale
Professor, Department of Civil Engineering, University of Sherbrooke, Sherbrooke, Canada

ABSTRACT

With the establishment of several construction applications of FRP reinforcement, there is a need for a system to resist lateral loads induced from wind and earthquake loads in these constructions. Reinforced concrete shear walls have shown effective performance in resisting lateral loads caused by wind and earthquake loads. Therefore, shear walls are frequently used in parking garages and multi-story buildings exposed to high lateral loading. This research involved testing a shear wall totally reinforced with FRP bars. Early information showed the inapplicability of reinforcing shear walls with FRP, but after overcoming the difficulties encountered, the results showed an opposite conclusion. The results obtained demonstrated significantly high utilization levels of the shear wall reinforced with FRP in term of drift, deformability, and failure mode.

The large scale shear wall experiment was carried out to examine the strength, stiffness and deformability by observing the degradation in stiffness and strength while resisting in plane reversed loading, and to measure the energy dissipation of the system accounting for the deformability of the shear wall. The shear wall specimen was in the medium-rise wall category where both flexural and shear deformations exist. The specimen was totally reinforced with glass FRP bars to resist flexure, shear, and sliding shear deformations.

KEYWORD
Glass FRP bar, concrete, shear wall, cyclic lateral loading, ductility, strength
Stiffness of FRP Pultruded Tubes under Repeated Axial Impacts

Ernesto J. Guades, Thiru Aravinthan, Md. Mainul Islam and Allan C. Manalo
Centre of Excellence in Engineered Fibre Composites, Faculty of Engineering and Surveying, University of Southern Queensland, Toowoomba, Australia

ABSTRACT

Fibre composites in deep foundation industry have been recognized to replace conventional materials such as concrete, steel and timber in harsh marine environment. The emergence of hollow fibre reinforced polymer (FRP) composite tubes as a structural component provided the industry to consider this material as a potential composite pile type as they can carry design load. However, issue such as driving performance of this material warrants investigation as they are considered the lowest performer among composite piles. The thin-walled section generally ruptures under high driving stresses, thus its stiffness for post-impact performance is in question. This paper experimentally investigated the effects of impact energy and number of impacts on the axial stiffness of hollow FRP composite tubes. Six incident energy variants were considered, and two specimens for a given impact energy were subjected to a maximum of 130 repeated impacts using a drop-weight impact tester. The impact response and the contact stiffness were evaluated in terms of damage progression and the evolution of peak force for both collapsed and non-collapsed tubes. Results point out that no significant difference exists in the behaviour of the tubes for which no collapse occurs with test duration. On the contrary, the location of the initiation of collapse influenced the shape of the load and number of impact curves for collapsed tubes. The value of the stiffness after the initiation of collapse remains the same regardless of the magnitude of the applied energy. Furthermore on the collapsed tubes, it was observed that impact energy does not significantly reduce the stiffness of tubes during initial impacts, however, their effects were apparent as the number of impacts increases.

KEYWORD

composite piles, FRP pultruded tubes, repeated impacts, collapsed tubes, drop-weight test
Seismic Control of Plastic Mechanism of Steel Reinforced Concrete Columns by the Use of GFRP Bars

Riyad S. Aboutaha
Associate Prof., Department of Civil & Environmental Engineering, Syracuse University, Syracuse, USA

Rafic G. El-Helou
Graduate Student, Dept. of Civil & Environmental Engineering, Syracuse University, Syracuse, USA

Manar S. Shraideh
Graduate Student, Dept. of Civil & Environmental Engineering, Syracuse University, Syracuse, USA

ABSTRACT

In order to limit the cost of seismic retrofit following an earthquake, it is recommended to shift the locations of potential plastic hinge regions away from the beam-column joints and foundation-column joints. Formation of a plastic hinge at the bottom end of a bridge column causes damage to the supporting foundation. Post-earthquake retrofit of bridge foundation is very difficult and expensive. In recent years, several techniques have been introduced to move the location of potential plastic hinge regions away from the joints. This has been done by the use of additional steel control reinforcing bars (rebars) extended over a certain length from the beam-column or the foundation-column joints. When used as control rebars, Glass fiber reinforced polymer (GFRP) rebars are superior to steel rebars in relocating plastic hinge regions, as they have lower modulus. In a steel reinforced concrete column, GFRP rebars could be used as control rebars, only. The primary advantage of the use of GFRP rebars is low bond stresses at the interface between the control rebars and the surrounding concrete, as a result, they cause significantly less damage to the column’s concrete core during a seismic event. This paper presents guidelines for the use of GFRP rebars for controlling the location of plastic hinge regions in steel reinforced concrete bridge columns. The recommendations are based on extensive study of the properties of concrete columns reinforced with hybrid reinforcements. These reinforcements consist of primary steel bars and auxiliary GFRP control bars. The results of this investigation suggest that GFRP bars are effective in shifting the plastic hinge regions in bridge columns subjected to axial load stress below 10 MPa.

KEYWORD

GFRP bars, bridge columns, seismic response, M-P interaction, shifting plastic hinge
Investigation of Flexural Performance of RC Beams
Strengthened with CFRP Textile and Cement Based Adhesives

Siavash Hashemi
Department of Civil Engineering, Monash University, Melbourne, Australia

Riadh Al-Mahaidi
Prof., Faculty of Engineering and Industrial Sciences,
Swinburne University of Technology, Melbourne, Australia

ABSTRACT

Strengthening of concrete structures with epoxy-bonded FRP composites is suitable for environments where the temperature is well below the glass transition temperature of the epoxy adhesive, $T_g$, which is normally in the range of 55-60°C. It is very beneficial if cementitious mineral-based bonding agents replace epoxy adhesives in order to produce a fire-resistant strengthening system.

Tests conducted by the authors have already shown that excellent reinforcement action can be achieved using cement-based adhesives. Tests included in the current paper investigated the flexural performance of strengthened beams at normal and high temperature. The strengthened RC beam with cement-based adhesive showed a considerable improvement in flexural performance at normal temperature. The strengthened RC beam with cement-based adhesive showed a considerable improvement in flexural performance at high temperature compared to the specimens with epoxy. The specimens with cement-based adhesive failed at temperatures nearly double of that with epoxy-based adhesive.

KEYWORD

FRP, strengthening, retrofitting, cement-based adhesives, fire resistance, high temperature exposure
Strengthening of Flat Plates with an Opening Using FRP Systems

Kiang Hwee Tan
Professor, Dept. of Civil & Environmental Engrg., National University of Singapore, Singapore

ABSTRACT

In structural upgrading, there are instances where openings need to be punched through existing floor slabs to accommodate new elevator shafts and stair wells. Creating holes in slabs would lead to a reduction in the strength and in some cases the stiffness of the floor system. The study reported in this paper was carried out to investigate the use of FRP systems in restoring the ultimate strength of reinforced concrete flat slabs in which an opening has been created. A total of five specimens, simulating the region around an interior column in a flat plate system, were fabricated. Each slab specimen measured 100 mm in thickness and had a short 250 mm square column stub at the center. One solid plate slab served as a reference specimen and the other four each contained an opening strengthened with FRP systems. The openings measured 500 mm by 500 mm and were located at two locations each along the diagonal and the mid-width of the slabs. The required FRP reinforcement was determined based on a pseudo-plastic analysis.

The slab specimens were supported over an effective span of two meters in both directions and subjected to a point load applied over the area of the column stub to failure. Test results showed that the ultimate strength of the slab was restored to that of the solid slab when the opening was placed along the diagonal at twice the effective depth from the column stub. The strength was about 85% that of the solid slab when the opening was diagonally adjacent to the column stub or when it was located along the mid-width at twice the effective depth from the column stub. For the slab with the opening located adjacent to the column stub at the mid-width, the strength restoration was about 60% only. Based on the study, recommendations on the appropriate location and strengthening of openings in flat plates are made.

KEYWORD

flat plates, FRP systems, openings, reinforced concrete, strengthening, tests
Effectiveness of a New CFRP Anchor in Preventing Delamination

Ahmed A.B. Mostafa, Ph.D., P.Eng.
Bridge Engineer, AMEC Environment & Infrastructures, Burlington, Ontario, Canada

A. Ghani Razaqpur, Ph.D., P.Eng.
Prof., Department of Civil Engineering, McMaster University, Hamilton, Ontario, Canada

ABSTRACT

A new CFRP anchor is developed and tested using full scale RC T-beams externally strengthened with multiple plies of a CFRP sheet. The anchor is made from a carbon fiber tow immersed in an epoxy resin. The anchor head is bonded by epoxy to the surface of the concrete in the vicinity of the FRP sheets and is designed to provide a relatively large surface for resisting interfacial shear stresses. The anchor legs are inserted into pre-drilled holes filled with epoxy adhesive. Four full scale T-beams, each 4880 mm long with span length of 4500 mm, were tested in four point bending. The beams cross-section had a total height of 400 mm and consisted of 500 mm wide by 100 mm thick flange and 250 mm wide web externally strengthened with either 4 or 8 plies of a CFRP sheet. Test results show that the anchor could prevent delamination even in the beams with 8 plies as failure was initiated by the rupture of the FRP. No sign of slippage and/or rupture of the anchors were observed. On the contrary, the companion beams without the anchors prematurely delaminated and they reached only a fraction of their theoretical strength.

KEYWORD

Anchors, Carbon Fiber, Delamination, FRP laminate, Interfacial Stresses, Reinforced Concrete Beams
Behavior of Laterally Restrained GFRP Reinforced Concrete Slab

Yu. Zheng
Department of Civil Engineering, Dongguan University of Technology, Dongguan, China

Chunhong Li
Department of Civil Engineering, Dongguan University of Technology, Dongguan, China

Guoyou Yu
Department of Civil Engineering, Dongguan University of Technology, Dongguan, China

ABSTRACT

The corrosion of reinforcement embedded in concrete bridge deck slabs has been the cause of major deterioration and of high costs in repair and maintenance. Fiber reinforced polymers (FRP) exhibit high durability in combination with high strength and light weight. The majority of research with FRP bars for reinforcing concrete has been on simply supported beams and slabs where the low value of elasticity of FRP has meant that the service behaviors has been critical. These differences have been attributed to the low value of elasticity of FRP compared to steel. However, laterally restrained slabs, such as those in bridge deck slabs, exhibit arching action or compressive membrane action (CMA), which has a beneficial influence on the service behaviors. Based on the previous research on CMA in steel reinforced concrete bridge deck slabs, a series of experimental tests of laterally restrained GFRP reinforced concrete slabs were carried out. Some structural parameters, including concrete strengths, reinforcement and boundary conditions, were investigated. Thereafter, an NLFEA model were established with a proposed failure criteria with consideration of brittle and sudden failure modes of GFRP reinforced concrete slabs. With the validation of experimental results, a good collection was obtained. A comprehensive study of CMA in this structural type was discussed.

KEYWORD

glass polymer fibers bars, concrete slab, compressive membrane action, experimental tests, NLFEA
Fatigue of Center Cracked Steel Plates with UHM CFRP Plate Strengthening

Chao Wu, Xiaoling Zhao, Wenhui Duan
Department of Civil Engineering, Monash University, Clayton, VIC 3168, Australia

Mohammad R. Emdad, Riadh Al-Mahaidi
Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

ABSTRACT

Composite materials have led to great advances in improving fatigue performance of steel structures over conventional strengthening methods. High modulus carbon fibre composites (CFRP) make this fatigue strengthening more promising by decreasing stress intensity factor range at the fatigue crack tip to a large extend. In this study, an ultra high modulus (UHM) CFRP plate, with a modulus of 460 GPa, was adopted to strengthen initially center cracked steel plates. CFRP strengthened steel plates were tested under fatigue loading to investigate the effectiveness of the composites on preventing fatigue crack propagation and extending the fatigue life. Five strengthening configurations were adopted by changing both the patch length and patch width. Both single-sided and double-sided strengthened specimens were tested. A crack detection method of “beach marking” was adopted during the fatigue tests, to monitor and record the crack propagation against fatigue cycles. Experimental results show that the application of UHM CFRP substantially reduces crack growth rate and prolongs fatigue life up to 8 times more than that of un-strengthened steel plates. It was also found that double-sided strengthening is more efficient than single-sided one. CFRP bond width, bond length and bond locations have considerable influences on the fatigue performance of strengthened steel plates.

KEYWORD

UHM CFRP plate, steel, fatigue, strengthening, crack propagation, experiment
Enhancement of Mechanical Performance of Steel/CFRP Adhesively-Bonded Joints at Elevated Temperatures through Carbon Nanotube Modification and Curing

Yu Bai
Dr., Department of Civil Engineering, Monash University, Melbourne, Australia

Tien C. Nguyen
Ph.D candidate, Department of Civil Engineering, Monash University, Melbourne, Australia

Chao Ding
Bachelor student, Department of Civil Engineering, Monash University, Melbourne, Australia

Xiao-Ling Zhao
Prof., Department of Civil Engineering, Monash University, Melbourne, Australia

ABSTRACT

Carbon fibre reinforced polymer (CFRP) has been considered as a promising approach to strengthen existing steel structures; such an adhesively-bonded system however exhibits a significant loss of stiffness and strength in an elevated temperature range. Carbon nanotube (CNT) modification and curing at elevated temperature are examined in this paper, in order to enhance the mechanical performance in the elevated temperature range. Steel/CFRP adhesively-bonded joints were prepared into four scenarios – 1) with and 2) without CNT modified epoxy adhesive cured at room temperature (20˚C) and 3) with and 4) without CNT modified epoxy adhesive cured at an elevated temperature (80˚C), and then tested in tension at temperatures from 20˚C to 80˚C. Enhancement of stiffness and strength in the elevated temperature range was not significant for the joints using CNT modified epoxy, while remarkable enhancement was found for the joints cured at the elevated temperature, comparing to those cured at room temperature.

KEYWORD

CFRP, Steel, Double Strap Joint, Temperature Effect, Carbon nanotube, Curing
Improving Fatigue Performance of CFRP Strengthened Steel Beams by Applying Vacuum Pressure in the Wet Layup of CFRP Woven Sheets

Hui Jiao
Lecturer, School of Engineering, University of Tasmania, Hobart, Australia

Xiao-Ling Zhao
Professor, Department of Civil Engineering, Monash University, Clayton, Australia
(National 1000-talent Chair Professor at Tsinghua University)

Fidelis Mashiri
Senior Lecturer, School of Engineering, University of Western Sydney, Sydney, Australia

ABSTRACT

Multiple layers of CFRP woven sheets are generally laminated through a wet layup process with epoxies being evenly distributed in each layer of CFRP sheets. Although attempts were made by researchers to evenly distribute epoxy resin in CFRP layers, the bonding quality is not easily controlled. Air bubbles or excessive epoxy resin may exist in hardened CFRP composites. As a result, the bonding strength may be affected. For the two types of CFRP materials that are commonly used in the strengthening of defected steel structures, CFRP woven sheets are required for curved sections, such as truck chassis and circular sections. The difference in the layup process of CFRP plates and CFRP sheets may contribute to the difference in fatigue life of repaired steel members. In this study, a vacuum bag was used to provide a negative pressure to suck out excessive epoxy resins and air bubbles during the wet layup process. The failure modes and fatigue life of steel beams strengthened with and without vacuum bags were compared. An increase in fatigue life was found to be ranging from 50% to nearly 4 times.

KEYWORD

wet-layup, vacuum bag, fatigue life, steel beam, CFRP woven sheets
Development of Reduction Technique of Thermal Stress Induced in CFRP Bonded Steel Plates

Toshiyuki Ishikawa
Assistant Prof., Department of Urban Management, Kyoto University, Kyoto, Japan

Atsushi Hattori
Associate Prof., Department of Urban Management, Kyoto University, Kyoto, Japan

Hirotaka Kawano
Prof., Department of Urban Management, Kyoto University, Kyoto, Japan

Takashi Nagao
Researcher, Research & Development Center, Nippon Light Metal Co., Ltd., Shizuoka, Japan

Akira Kobayashi
General Manager, Composites Company, Nippon Steel Materials Co., Ltd., Tokyo, Japan

ABSTRACT

In CFRP bonded onto steel plates, thermal stress is induced in steel plate by temperature change, due to difference in coefficients of linear thermal expansion between steel and CFRP plates. In this study, reduction technique of the thermal stress in steel plate strengthened by CFRP plate, which is additional bonding of aluminum alloy plates, is proposed. Namely, the coefficient of linear thermal expansion of laminated plate consisted of CFRP and aluminum plates is designed as that of steel. In this study, to verify the effectiveness of proposed method, heat tests of CFRP and aluminum plates bonded onto steel plate were carried out. As a result, infinitesimal thermal stresses in steel plate with CFRP and aluminum alloy plates were measured while large thermal stress was measured in conventional CFRP bonded steel plate.

KEYWORD

CFRP plate, thermal stress, aluminum alloy plate, steel plate, heat test
Mechanical Characteristics of CFRP Reinforcement for Corroded Steel under Axial Tension

Yukihiro Matsumoto, Nguyen Duc Long, Seishi Yamada

Dept of Architecture and Civil Engineering, Toyohashi Univ. of Tech., Toyohashi, Japan

and Takahiro Matsui

Advanced Composites Technical Dept, Toray Industries, Inc., Nagoya, Japan

ABSTRACT

Carbon fiber reinforced polymer (CFRP), which has some properties of light weight, high strength and high durability, has been applied to many concrete structures as repair, strengthening and seismic retrofitting. In recent days, the studies on its application to steel structures have also been developing for opened sectional members such as I-shaped beams. However, nowadays, it is a remarkable attention that the mechanical performance of steel members are degraded due to corrosion by decreasing cross-sectional area of steel pipe inside the section along with time. Then the repairing of the corroded steel pipes on the outside section is particularly required and CFRP has expected to apply in repairing and strengthening procedure.

In this paper, the strength of corroded steel plates and the effect of repair with CFRP are investigated through finite element analyses (FEA) and longitudinal tensile tests. First, the tensile tests of steel plates having partial loss of area are carried out. Second, strength, yield load and behavior of stress concentration are made clear through the tensile tests and FEA. Finally, CFRP is adhesively bonded to corroded steel plate on the other side of corrosion, and then the effects of repair with CFRP are discussed in detail. The results confirmed that axial stiffness and yield stress increases using FRP even if it is adhesively bonded to corroded steel plate on the other side of corrosion. It would be suggested that the present repairing method provides the reasonable and useful procedure for reinforcing the corroded steel members.

KEYWORD

FRP reinforcement, corroded steel, axial tension, FEA
Prediction of the Flexural Behavior of Fibre Composite Sandwich Beams

Allan C. Manalo¹, Thiru Aravinthan² and Karu Karunasena²

Research and Teaching Fellow¹, Associate Professor², Centre of Excellence in Engineered Fibre Composites, University of Southern Queensland, Toowoomba, Queensland 4350, Australia

ABSTRACT

One of the core assumptions underlying the construction industry is that the true potential of fibre composite sandwich structures can only be exploited through the use of complex mathematical theories and sophisticated analysis techniques. Research experience at the Centre of Excellence in Engineered Fibre Composites at the University of Southern Queensland has shown that with correct material data, the behaviour of composite sandwich structures can be analysed within acceptable levels of confidence using simple techniques. In this paper, a simplified Fibre Model Analysis (FMA) to describe the approximate behavior and the governing failure mechanisms of composite sandwich structures under flexural load is presented. This fundamental design methodology is based on sectional equilibrium, strain compatibility, and the constitutive material behaviour using a layer-by-layer approach to evaluate the sectional forces and to calculate the nominal flexural capacity of a composite sandwich section. An important advantage of the proposed model is that it can account for the nonlinear behaviour of the core in compression, the effect of core cracking in tension and the linear elastic behaviour of the fibre composite skins. This method also allows analysing composite sandwich structures with non-symmetric section and using only MS Excel spreadsheet program. The efficiency and practical application of this prediction equation is demonstrated by analysing the behavior of individual and glue-laminated composite sandwich beam structures made from the glass fibre composite skins and phenolic core material and comparing with the results of experimental investigation and numerical simulation. This method was found to reasonably describe the behavior of the fibre composite sandwich structures in flexure, therefore suggested as very useful for engineering design and calculations.

KEYWORD

Sandwich structures, fibre composites, Fibre Model Analysis, design methods, flexure
Performance of newly Developed CFRP Precast Prestressed Decked Bulb T Beams

Nabil Grace
Dean, College of Engineering, Lawrence Technological University, Southfield, MI, U.S.A.

Tsuyoshi Enomoto
Manager, Tokyo Rope Manufacturing Co. Ltd. Tokyo, Japan

Prince Baah
Graduate Student, Center for Innovative Materials Research (CIMR), Lawrence Technological University, Southfield, MI, U.S.A.

Mena Bebawy
Post-Doctoral Research Fellow, Center for Innovative Materials Research (CIMR), Lawrence Technological University, Southfield, MI, U.S.A.

ABSTRACT

This study introduces an innovative scheme of bridge superstructure for expedited construction, improved inspection, serviceability, and extended lifespan. The new bridge superstructure is assembled from precast prestressed decked bulb T beams reinforced and prestressed with corrosion-free fiber reinforced polymer (FRP) materials. An experimental investigation accompanied by a numerical simulation was developed to evaluate the performance of the newly developed beams. Through the experimental investigation, three single decked bulb T beams were constructed and tested to failure. The first beam served as a control beam and was prestressed and reinforced with conventional steel strands and reinforcing bars. The second and third beams were prestressed and reinforced with carbon fiber composite cables (CFCC) strands and carbon fiber reinforced polymer (CFRP) tendons, respectively. The investigation revealed that the performance of beams reinforced with CFCC strands or CFRP tendons is comparable with the performance of the control beam at both service and ultimate limit states. All three beams exhibited high load carrying capacity with large corresponding deflection and fair amount of absorbed energy before failure. The study showed that the corrosion-free FRP-reinforced decked bulb T beams can be safely deployed in construction to enhance the performance and extend the lifespan of bridge superstructures.

KEYWORD

carbon fiber reinforced polymer, prestressed, precast concrete, flexural, T beams
Effects of the Material Constants of Bond on Stress Distributions for FRP/ALC Sandwich Slabs

Seishi Yamada, Takeshi Seino, Yukihiro Matsumoto and Hideo Oka
Department of Architecture and Civil Engineering, Toyohashi University of Technology, Toyohashi, Japan

ABSTRACT

The slabs are one of the heaviest structural elements in bridges or buildings, therefore, various lightweight-slab systems, i.e. using lightweight concrete or installing voids, have been proposed for the increase of the seismic load-carrying capacity of these civil structures. However, in these conventional trials, the weight reduction ratios against the same thickness concrete slabs were less than around 20%. The innovative sandwich panel systems for weight reduction, for the increase of the bending rigidity, and for the improvement of corrosion resistance in long-life uses, are studied in this paper. The herein proposed sandwich panels consist of FRP surface skins and an ultra-lightweight ALC (autoclaved lightweight aerated concrete) core the density of which is very small and may be around 0.5 g/cm³. The FRP material would be a very suitable material for anti-corrosion, lightweight and high strength, especially when applied to bridge slabs.

In order to grasp the fundamental structural behaviors of these FRP/ALC sandwich slabs, various finite element analyses for four-point bending loading models are performed in this paper. The adopted variables in the FE analysis are Young’s modulus of bond, the thickness and the width of FRP skins. Consequently, it has been shown that the classical simple composite beam theory is available to estimate the deflection behaviors for the Young’s modulus ratio $E_a / E_s \geq 10^{-3}$ which is satisfied by normally used epoxy bonds. In addition, this paper discusses that as the Young’s modulus of FRP increases, the maxima of normal stress and shear stress at the side surface of the ALC core decrease significantly even though stress concentration occurs near the edge of bond layer.

KEYWORD
sandwich slab, FRP skin, ALC core, local stress concentration, effect of bond stiffness
The Use of FRCC and FRP for the Joining Method of Permanent Formwork

Qingxu JIN\textsuperscript{1}

Christopher K. Y. Leung\textsuperscript{2}

\textsuperscript{1,2}Department of Civil and Environmental Engineering of HKUST, HKSAR, China

ABSTRACT

Formwork elements, fabricated with pseudo-ductile cementitious composites (PDCC) and embedded glass fiber reinforced polymer (GFRP) reinforcement has been developed recently. A novel jointing method, involving the embedment of GFRP in high-strength fiber reinforced cementitious composites (HSFRCC), is studied in this paper. The background of permanent formwork is firstly reviewed. The determination of the joint width (i.e. the required embedded length of GFRP bar) to obtain the interfacial parameters, which governing the bond capacity between HSFRCC and GFRP bars, is briefly described. In order to further develop and verify the joining method, beam members with joined and monolithic PDCC formwork are prepared and tested under four point bending. The comparison between joined and monolithic formwork indicates that almost 95\% of the load capacity can still be achieved even with the presence of the joint in the formwork. Besides, the ultimate load of joined formwork is higher than the value obtained from conventional reinforced concrete design calculations. Therefore, the feasibility of the joining method for practical applications is verified.

KEYWORD

formwork, cementitious composite, joining method
Structural Behavior of Composite Girders Consisting of Hybrid FRP I-Beam and Precast Ultra High Performance Fiber Reinforced Concrete Slab

Hiroshi Mutsuyoshi
Prof., Dept. of Civil and Environmental Engineering, Saitama University, Saitama, Japan

Nguyen Duc Hai
Research Associate, Dept. of Civil and Environmental Engineering, Saitama University, Saitama, Japan

Zhishen Wu
Prof., Dept. of Urban & Civil Engineering, Ibaraki University, Ibaraki, Japan

ABSTRACT

Hybrid Fiber Reinforced Polymer (HFRP), which is composed of Carbon FRP (CFRP) and Glass FRP (GFRP) has several advantages such as light weight, high specific strength, and corrosion resistance. This material is expected to find its application in severe corrosive environments or where lightweight rapid construction is required. This paper presents the development of composite girders using HFRP I-beam and precast Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) slab. UHPFRC has high strength and high ductility allowing for a reduction in the cross-sectional area and self weight of the girder. A number of full-scale flexural beam tests were conducted using different dimensions of slab and with/without epoxy bonding between the slab and HFRP I-beam. The test results suggested that the flexural stiffness of composite girders with the combined use of bolts and epoxy bonding as shear connectors is higher than those with solely bolt-connectors. Delamination failure was not observed in the compressive flange of the HFRP I-beam and the high tensile strength of CFRP in the bottom flange was effectively utilized with the addition of the UHPFRC slab on the top flange.

KEYWORD

Composite girder; hybrid fiber reinforced polymer; ultra-high performance fiber-reinforced concrete; flexural stiffness
Influence of Environmental Temperature for Bond Strength between CFRP Sheet and Concrete

Yasuhiro Koda
Associate Prof., Department of Civil Engineering, Nihon University, Fukushima, Japan

Akihisa Kamiharako
Assistant Prof., Graduate School of Science and Technology, Hirosaki University, Hirosaki, Japan

Ichiro Iwaki
Prof., Department of Civil Engineering, Nihon University, Fukushima, Japan

ABSTRACT

The aim of this study is to evaluate the bond strength between CFRP sheet and concrete during a specified period when either a cyclic temperature or a constant temperature is applied. As the results of experiments, it was found that the bond strength decreased under a high constant temperature or a high and a low cyclic temperature. The bond strength degradation in the case of the constant temperature depends primarily on the deterioration of the bonding strength of the epoxy resin adhesive. However, in the case of the cyclic temperature, the different coefficients of linear expansion of concrete and CFRP seem to influence the strain behavior.

KEYWORD

bond strength, environmental temperature, CFRP sheet, coefficient of linear expansion
Effect of Adhesive Viscoelasticity on the Creep Behaviour of FRP Strengthened Concrete Beams

Ehab Hamed
Lecturer., Center for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia

ABSTRACT

This paper focuses on the effect of the viscoelasticity of the adhesive layer on the flexural creep response of reinforced concrete beams strengthened with composite materials. A theoretical model is developed, which considers the strengthened beam as a layered structure that consists of the reinforced concrete beam, the adhesive layer, and the FRP strip, and accounts for the creep of each component. The model also accounts for cracking and tension-stiffening of the reinforced concrete and for the deformability of the adhesive layer in shear and through its thickness, which allows the evaluation of the edge and interfacial stresses. A parametric study of different viscoelastic material properties of the adhesive is presented, and their effect on the time variation of the internal forces and edge stresses is investigated.

KEYWORD

Adhesive, Composite materials, Concrete, Creep, FRP, Strengthening, Viscoelasticity
Durability of Aramid and Carbon FRP PC Beams under Tidal and Thermal Accelerated Exposure

Hiroshi Nakai, P.E.Jp
General Manager, MAEDA KOSEN CO., LTD., Tokyo, Japan

Hirofumi Watanabe, P.E.Jp
Manager, Kawada Construction Co., LTD., Tokyo, Japan

Tsuyoshi Enomoto
Manager, TOKYO ROPE MFG. CO., LTD., Tokyo, Japan

Taketo Uomoto, Dr.Eng.
Chief Executive, Public Works Research Institute, Japan

ABSTRACT

The authors present results from 300 cycles of accelerated drying and wetting exposure studied during six years to assess the effect of tide and temperature variation cycles on the durability. In this study, prestressed concrete (PC) beams were reinforced with Fiber Reinforced Polymer (FRP) and steel strand tendons. The FRP tendons considered in this study are aramid and carbon fiber polymer tendons. It is found that FRP tendons degraded due to the difference between thermal expansion coefficient of FRP tendons and concrete. Moreover, organic fibers and resins were hygroscopic materials which caused decomposition by reaction with water. The PC beams were placed in a circulating water tank which carried out under repeated temperature and humidity cycles for seven days.

The effect of drying and wetting exposure was evaluated from bending test conducted after 150 and 300 cycles. The effect of the exposure showed in deterioration of bond and decrease of effective prestressing force of the PC steel beams. Moreover, the envelope curves of the PC steel beams were deteriorated. The PC beams with FRP tendons showed better performance than that of PC beams reinforced with steel tendon regarding the effective prestressing force and flexural capacity.

KEYWORD

exposure test, tide, temperature, aramid, carbon
Imperfection Influence on FRP-Plated RC Beams

Y. C. Guo and G. M. Chen

Associate Prof., Dr., Guangdong University of Technology, Guangzhou, China

L. J. Li and F. Liu

Prof., Guangdong University of Technology, Guangzhou, China

B. Yuan and F. M. Ren

Associate Prof., Guangdong University of Technology, Guangzhou, China

P. Y. Huang

Prof., South China University of Technology, Guangzhou, China

ABSTRACT

This paper presents a finite element (FE) study on the effects of imperfections in the adhesive layer on the bond behaviors of the FRP-to-concrete bonded interface in an FRP-plated beam. An FE model with imperfections in adhesive layer was proposed in which the adhesive layer was modeled as an elastic material, and the interfacial bond behavior between concrete and adhesive was modeled based on Lu et al.’s bilinear bond-slip relationship. Based on the FE model, the influences of size and location of the imperfections on the interfacial bond behaviors (e.g. stress distributions) were investigated for non-prestressed FRP and prestressed FRP respectively. The research results show that in the pre-stressed FRP case, the existence of imperfections leads to larger variations of the stress distributions in the adhesive layer at the boundaries of the imperfections compared with the non-prestressed FRP case.

KEYWORD

fiber-reinforced polymer (FRP), RC beams, adhesive imperfection, interfacial stress
Fatigue Performance of Hybrid CFRP-GFRP-UHPC Beams

Donna S.M. Chen
Ph.D. Candidate, Department of Civil Engineering, University of Calgary, Calgary, Canada

Raafat El-Hacha
Associate Professor, Department of Civil Engineering, University of Calgary, Calgary, Canada

ABSTRACT

The number of experimental investigations into the performance of structural members constructed using a combination of high performance materials have been increasing with recent years. One of the main advantages of high performance materials over conventional building materials is their resistance to corrosion. This research program examined the behaviour of innovative hybrid beams composed of different Fibre Reinforced Polymer (FRP) materials as well as Ultra-High Performance Concrete (UHPC) under cyclic flexural loading. Three beams were tested and it was found that the hybrid beams were capable of sustaining comparable strength under fatigue loading as to when subjected to monotonic loading. The findings also indicated that design considerations should be made for the occurrence of increased strains and deflections during the initial 40,000 cycles of testing as well as for the residual deformations and softening that occurs in the hybrid beam during the period prior to ultimate failure, most probably due to the initiation of internal microcracking in the matrix of the FRP material.

KEYWORD

fibre reinforced polymer, glass, carbon, ultra-high performance concrete, hybrid, fatigue,
Size Effect of Square Concrete Columns Confined with CFRP Wraps

Zhenyu Wang  Daiyu Wang
School of Civil Engineering, Harbin Institute of Technology, Harbin, China

Scott Thomas Smith
Department of Civil Engineering, The University of Hong Kong, Hong Kong, China

ABSTRACT

Most of the previous research conducted on concrete columns confined with fiber-reinforced polymer (FRP) composites has been based on small sized specimens. Such sizes can result in the FRP confinement relative to the concrete component to be significantly stiffer than practical retrofit applications. In addition, few investigations have confirmed the validity of extrapolating small-scale specimen results to large-scale specimen results. In this study, nine square concrete columns wrapped with carbon fiber-reinforced polymer (CFRP) composites were divided into five groups and tested under concentric axial monotonic compressive loading. In each group, the specimens consisted of two different cross-sectional dimensions but the same lateral confinement pressure according to ACI440-2R Code. The experimental results showed that for specimens with different cross-sectional dimensions but same lateral confinement, there were significant differences in the compressive strength and axial stress-strain responses. The confinement of CFRP wraps resulted in significant increases in both the axial strain and stress capacity of confined small-sized columns, while significant enhancement in axial strain but only slightly increases in axial stress for large-sized square columns were observed. All axial stress-strain responses exhibited the same bilinear ascending trend, however, the slope of the second linear portion of the large-sized columns was smaller than that of the small-sized columns.

KEYWORD

fiber reinforced polymer, confined concrete, square columns, size effect, stress-strain behavior
Shear Strengthening of Full-Scale RC T-Beams with CFRP Sheets

Abdeldjelil Belarbi
Professor and Chair, Department of Civil and Environmental Engineering, University of Houston, Texas, USA

Michael Murphy
Structural Engineer, CTL Group, Washington, D.C., USA

Sang-Wook Bae
Assistant Professor, Department of Civil and Environmental Engineering, Texas Tech University, Texas, USA

ABSTRACT

Many research studies have been conducted to investigate the behavior of reinforced concrete (RC) beams strengthened in shear with externally bonded fiber-reinforced polymer (FRP) composite materials over the past two decades. As a result, analytical models and design equations are available in the form of code/guidelines/specifications in the United States and other countries. However, most of the existing studies were conducted on small-scale specimens. Thus, analytical models and design equations developed from those studies may not be able to predict the shear capacity of large-scale RC beams strengthened in shear with externally bonded FRPs. This study was, therefore, performed to evaluate the performance of existing analytical models and design equations with the test results from eight full-scale RC T-beams as well as the experimental database consisting of 375 test results obtained from existing literature. The results of the full-scale tests conducted in this study indicated that FRP shear strengthening on full-scale RC beams is as effective as that observed on small-scale RC beams. The performance of the analytical models considering the effective strain concept appeared to be more reliable to predict the shear strength for both small- and large-scale beams than the ones considering non-uniform distribution of strains in FRP.

KEYWORD

shear, T-beam, FRP, strengthening
Shear Strengthening of RC Beams Using Hybridized FRP Composite

Sang-Su Ha
Assistant Professor, Department of Architectural Engineering, Kangnam University, Yongin 449-702, Korea

Dong-Uk Choi
Professor, Department of Architectural Engineering, Hankyong National University, Anseong 456-749, Korea

Thomas H.-K. Kang
Assistant Professor, Department of Architecture and Architectural Engineering, Seoul National University, Seoul 151-744, Korea

Chin Yong Lee
President, Carecon, Daekyeong Building 2F, 563, Seongnae-dong, Gangdong-Gu, Seoul, Korea

ABSTRACT

This study investigated the effect of shear strengthening of reinforced concrete (RC) beams using hybridized Fiber Reinforced Polymer (FRP) composite. The hybridized FRP composite (HF) consisted of glass fiber (GF) and carbon fiber (CF). The HF can be more economical than CF and demonstrates pseudo-ductility when subjected to tension. A total of seven RC beam specimens were manufactured and tested in shear. Test variables were the type of fibers (CF, GF, and HF), method of shear strengthening (U-wrap, I-type, and U-wrap+I-type), and amount of fibers. All specimens were subjected to four-point loading. A control beam without any shear reinforcement failed by shear in the shear span. All specimens shear-strengthened with CF, GF, or HF sheets failed by debonding of the FRP from the concrete substrate. The failure experimentally determined loads matched closely with those theoretically predicted using ACI 440.2R-08 equations. Based on the results of the tests, the quantitative effects with shear strengthening were from 56% to 137% higher than BS-N without any shear strengthening, and the specimens with the mixed U-wrap and I-type showed the most shear strengthening effects in terms of ultimate strength. However, the U-wrap method was more effective when the strengthening effect was evaluated based on the amount of fibers used.

KEYWORD

Shear strengthening, hybridized FRP composite (HF), glass fiber (GF), carbon fiber (CF), pseudo-ductility
Short Term Creep Tests of Low Strength Rectangular Concrete Members Jacketed with Carbon FRP Sheets

Cem Demir
PhD Cand., Struct. And Earthquake Eng. Lab., Dept. of Civil Eng., Istanbul Tech. Univ., Istanbul, Turkey

Aygul Aydogmus
Researcher, Struct. And Earthquake Eng. Lab., Dept. of Civil Eng., Istanbul Tech. Univ., Istanbul, Turkey

Alper Ilki
Prof., Struct. And Earthquake Eng. Lab., Dept. of Civil Eng., Istanbul Tech. Univ., Istanbul, Turkey

ABSTRACT

Usage of low strength concrete is common in many developing countries all around the World. For example, in Turkey, the approximate average concrete compressive strength of existing reinforced concrete buildings constructed before 1990s is around 10 MPa. Since the concrete strength is foreseen higher during structural design, the sustained axial stresses of columns of such existing buildings may be remarkably high (70–90% of axial capacity). These high axial stresses sometimes cause collapse of columns or overall structure due to effects of creep of concrete. The service life of such structures can be enhanced through external jacketing of columns with FRP sheets. The efficiency of such a rehabilitation is higher in case of low strength concrete. In this study, the short term creep behavior of carbon FRP sheet jacketed low strength (~7 MPa) rectangular concrete prisms is investigated under varying levels of sustained axial stresses. The safe lifetime of the specimens are extrapolated considering the variations in axial and transverse strains measured during short term creep tests (48–96 hours). In addition, the residual capacities of carbon FRP jacketed rectangular prism specimens are investigated after being subjected to short term creep tests.

KEYWORDS

carbon fiber, confinement, low strength concrete, rectangular cross-section, retrofit, creep, sustained loading
Bond and Force Transfer of FRP Materials Bonded to Concrete Using Sitecure System

Rebecca J. Gravina
Senior Lecturer, School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia

S. Ali Hadigheh
Ph.D. Candidate, School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia

Sujeeva Setunge
Associate Professor, School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia

ABSTRACT

Use of Fibre Reinforced Polymer (FRP) materials to strengthen existing structures has been investigated over the past two decades. Experimental and analytical programs have acknowledged the effectiveness of this retrofitting strategy to improve the behaviour of structures under seismic loads. However, debonding of FRP from the substrate in strengthened members has limited their application. Different methods have been proposed to achieve a sufficient bond between FRP materials and concrete members. In this article, the results of the preliminary single shear push-pull tests of FRP jointed prisms using an innovative technique, called SiteCure, will be discussed. In the SiteCure technique, vacuum consolidation and heat cure are employed to provide a superior bond, which is more durable against external loads. Preliminary results of the bond behaviour, ultimate load capacity and failure mode of specimens retrofitted by traditional methods will be compared with those of SiteCured specimens.

KEYWORD

Sitecure, FRP, single shear push-pull test, concrete prisms, wet lay-up, pultruded plates
Bonding of Varying-thickness FRP Laminates to RC Beams

P. Fakhrimoghadam
Ph.D. Candidate, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran
Senior Engineer, Sazeh Consultants, Tehran, Iran

A. Vafai
Prof., Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

ABSTRACT

Effect of varying FRP thickness (number of layers) through its bond to RC beam on bond characteristics is investigated in this paper. The paper benefits from finite element solutions introducing equivalent strut model for adhesive layer. Shear and normal stresses of adhesive layer and interaction of these stresses are involved in this model. Nonlinear behavior of materials including crack/crush in concrete and softening in adhesive is considered. The present model is verified against an empirical model and good consistency is observed between two models. Consequently, interfacial stress distribution toward the bond and softening initiation and deboning initiation and failure loads are evaluated. Also, beam deflection and debonding energy dissipation are monitored as well. Following, effect of decreasing FRP thickness at two ends of interface on beam load capacity and deformability prior to failure is studied. It is concluded that appropriate configuration for trim points of FRP layers can improve abovementioned properties of beams. The results of the paper provide practical guides to use FRP laminates with varying thicknesses to strengthen RC beams.

KEYWORD

tapered FRP, bond stress, finite element method, interfacial stresses, plate end debonding
Bond Properties between Continuous Fiber Rope and Concrete

Kenzo Sekijima
Researcher, Institute of Science and Technology, Kanto Gakuin University, Kanagawa, Japan

Kyouhei Kawakami
Engineer, Raito Kogyo Co., Ltd., Tokyo, Japan

Junichi Izumo
Prof., Civil and Environmental Engineering Department, Kanto Gakuin University, Kanagawa, Japan

ABSTRACT

Continuous Fiber Rope is made of Aramid fiber or Vinylon fiber and shaped in the form of rope as reinforcement for concrete members. It is characterized by a lightweight, a high tensile strength and an excellent durability compared with reinforcing steel bar. It has also a good transportability, and it is flexible to be easily arranged at a construction site. The authors have already investigated not only the tensile properties of Continuous Fiber Rope but also the capacities of some kinds of splice of Continuous Fiber Rope. In this research, in order to investigate the bond properties between Continuous Fiber Rope and concrete the pull-out tests of Continuous Fiber Rope with small diameter and large diameter were carried out. The bond strength of Continuous Fiber Rope was much lower than that of a deformed steel bar. Moreover, the slippage of the free end of Continuous Fiber Rope was much larger than that of a deformed steel bar.

KEYWORD

Continuous Fiber Rope, Aramid fiber, Vinylon fiber, bond property, pull-out test
Bond Strength of Carbon and Aramid Fiber Reinforced Polymer Rebars in Normal Strength Concrete

So Jeong Han
Graduate Student, Department of Architectural Engineering, Kyung Hee University,
Yongin, Korea

Dae-Jin Kim, Young Hak Lee
Assistant Professor, Department of Architectural Engineering, Kyung Hee University,
Yongin, Korea

Heechul Kim
Professor, Department of Architectural Engineering, Kyung Hee University,
Yongin, Korea

ABSTRACT

The bond behavior of reinforcing bars is an important issue in the design of reinforced concrete structures and the use of fiber reinforced polymer (FRP) rebars is a promising solution to handle the problems of steel reinforcement corrosion. This study investigates the bond characteristics of carbon and aramid FRP (CFRP and AFRP) bars embedded in normal strength concrete. A pull-out test was performed on 33 normal strength concrete specimens reinforced with FRP and steel bars with different embedment lengths. The average bond stress versus slip curve is plotted for each type of specimens and their failure modes are identified. The effect of embedment length of an FRP rebar on its bond strength is also examined in this work.

KEYWORD

FRP rebars, carbon fiber, aramid fiber, bond strength, pull-out test, embedment length
Investigation of the Bond Behavior for the Embedded Through-Section FRP Rod Shear-Strengthening Method

Ahmed Godat
Department of Construction Engineering, École Technologie Supérieure, Montreal, Canada

Amar L’hady
Department of Construction Engineering, École Technologie Supérieure, Montreal, Canada

Omar Chaallal
Department of Construction Engineering, École Technologie Supérieure, Montreal, Canada

Kenneth W. Neale
Department of Civil Engineering, Université de Sherbrooke, Sherbrooke, Canada

ABSTRACT

The embedded through-section (ETS) method is a new shear strengthening technique recently developed to avoid the debonding failure that occurs with other FRP strengthening techniques such as those using externally bonded (EB) and near-surface-mounted (NSM) FRPs. The technique offers greater confinement and leads therefore to a substantial improvement in bond performance. In this study, experimental results from 13 direct-shear test specimens are reported. The influence of the following major parameters on the bond behavior of FRP-strengthened reinforced concrete beams is examined: concrete strength, quantity of epoxy adhesive, bar diameter, bar surface type, and bar bond length. The impact of these parameters is summarized in terms of the failure mode, ultimate bond force and bond force–slip relationships. The experimental results show that debonding can be avoided by providing a sufficient bar length and concrete strength. As a result, designers will be able to avoid debonding failures and to develop the full capacity of shear-strengthened beams.

KEYWORDS

ETS method; shear-strengthening; direct shear test; experimental; parametric study
Analysis and Design of Perforated SIFCON Blocks for Compression Yielding Structural Systems

Yufei Wu
Associate Prof., Dept of Civil and Architectural Engineering, City University of Hong Kong, Hong Kong, China

Jiafei Jiang
PhD student, Dept of Civil and Architectural Engineering, City University of Hong Kong, Hong Kong, China

Kang Liu
Senior research associate, Dept of Civil and Architectural Engineering, City University of Hong Kong, Hong Kong, China

ABSTRACT

Compression yielding (CY), an innovative structural concept, has recently been introduced to offset the ductility deficiency of concrete structures reinforced with fiber-reinforced polymer (FRP). The CY structural scheme employs a ductile material or a mechanism to replace concrete in the compression zone of a plastic hinge, thus allowing ductile flexural deformation of CY members to be achieved through the compressive, rather than tensile, yielding of a member. Experimental study has demonstrated that the extremely high ductility demand of the CY material can be satisfied by providing perforations inside a slurry infiltrated fiber concrete (SIFCON) block. This paper reports the analytical work that has been conducted to study the perforation effect on the strength and ductility of SIFCON blocks. Furthermore, a methodology has been proposed for the design of the perforated SIFCON block to achieve a given strength and ductility requirement.

KEYWORD

Compression yielding (CY), FRP, SIFCON blocks, Perforation, Strength, Ductility
Improvement of Debonding Bending Moment of Pre-tensioned CFRP Plates Bonded onto Steel Members

Masaru Shimizu
Graduate student, Department of Urban Management, Kyoto University, Kyoto, Japan

Toshiyuki Ishikawa
Assistant Prof., Department of Urban Management, Kyoto University, Kyoto, Japan

Atsushi Hattori
Associate Prof., Department of Urban Management, Kyoto University, Kyoto, Japan

Hirotaka Kawano
Prof., Department of Urban Management, Kyoto University, Kyoto, Japan

ABSTRACT

Recently, some research reports on the applications of pre-tensioned CFRP plates on steel members have been published. As well as applying the bending moment, however, releasing the pre-tension of the CFRP plate provide high shear and peel stresses at the adhesive ends. Therefore, in strengthening of steel members with pre-tensioned CFRP plates, the CFRP plates tend to have easily debonding than non pre-stressed one. In this study, to reduce its shear and peel stresses at the adhesive ends due to releasing the pre-tension of the CFRP plates, installing non pre-tensioned regions in the CFRP plate is proposed. To verify whether the proposed method is effective, theoretical investigation was carried out under the simple loading condition of pure bending. It is found that the shear stress at the adhesive ends by releasing pre-tension of CFRP plate becomes almost 0 in proposed method. Therefore, the applicable limit of bending moment and pre-tension for prevention of debonding of CFRP plate is improved compared with conventional pre-tension method. Additionally, a design method of required length of the non pre-stressed regions is also presented.

KEYWORD

CFRP plate, non pre-tensioned region, debonding bending moment, steel member
Mechanical Behaviour of a New Type of Fibre Composite Railway Sleeper

Allan C. Manalo\(^1\) and Thiru Aravinthan\(^2\)

Research and Teaching Fellow\(^1\), Associate Professor\(^2\), Centre of Excellence in Engineered Fibre Composites, University of Southern Queensland, Toowoomba, Queensland 4350, Australia

ABSTRACT

This paper presents the results of an experimental investigation on the flexural and shear behaviour of a new type of fibre composite sleeper for railway turnout application. The building block of this innovative railway sleeper is a new generation composite sandwich structure made up of glass fibre composite skins and modified phenolic core material that has been specifically developed for civil engineering applications. Three different section configurations for railway sleepers were produced by gluing layers of fibre composite sandwich structure together in flatwise (horizontal) and in edgewise (vertical) orientations and tested under 4-point static bending and asymmetrical beam shear tests. The effects of the orientation of sandwich lamination on the mechanical behavior of sleepers were investigated. The capacity of the fibre composite sleepers in holding spike-screws was also evaluated. The results showed that the orientation of sandwich laminations has a significant effect on the mechanical behavior of fibre composite railway sleepers. The sleeper section with glued sandwich structures in the edgewise position presented appropriate strength and stiffness for railway sleeper application and has high resistance to hold screw spikes. The mechanical properties of the fibre composite sleeper are far better than most of the available composite railway sleepers and are comparable with the existing timber turnout sleepers demonstrating that the new fibre composite sleeper is a viable alternative sleeper material for railway turnouts.

KEYWORD

Fibre composites, sandwich structures, railway sleepers, flexure, shear
Gravimetric Experimental Study on Moisture Diffusion Characteristic of Pultruded FRP Composite and Adhesives

Xu Jiang
PhD student, Section of Structural and Building Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands

Henk Kolstein
Associate Professor, Section of Structural and Building Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands

Frans S.K. Bijlaard
Professor, Section of Structural and Building Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands

ABSTRACT

Pultruded FRP composite material was increasingly used in the applications of civil infrastructures, especially for bridge decks. Thus, the long-term life of these materials in hostile environments is critical. In this paper, experimental studies have been undertaken to characterise the moisture diffusion of pultruded FRP composite materials and adhesives. Gravimetric experiments were carried out for the rectangular FRP composite specimens, which were exposed to the vapour environmental condition and also immersed in water. Moisture uptake curves as a function of time were obtained. Correspondingly, based on the moisture diffusion theory, the diffusion coefficients of FRP composite material parallel to the pultrusion direction were identified. All the FRP specimens reached the moisture saturation level within two days. Comparing with the moisture diffusion process in different aging conditions, the conclusion can be drawn that the rates of moisture uptake are more sensitive to temperature and the moisture saturation levels of FRP material are only dominated by relative humidity and immersed water. For the gravimetric experiments of adhesive specimens, after 37 day environmental ageing, only polyurethane adhesive material reached the moisture equilibrium as 2.667% of the initial self-weight within 6 days. This value is much higher than that of FRP material in the same ageing condition of 40°C, 96% RH. But the moisture diffusion process into adhesives is quite slower.

KEYWORD

pultruded FRP composite, adhesive, moisture diffusion, environmental effects
Practical-Orientated Full-Scale Tests In Comparison With Bond Checks Of Different Guidelines

Wolfgang Finckh
Research assistant, Department of Civil Engineering and Geodesy, Institute of Building Materials and Structures, Chair of Concrete Structures, Technische Universität München, Munich, Germany

Konrad Zilch
Full Professor Emeritus, Department of Civil Engineering and Geodesy, Institute of Building Materials and Structures, Chair of Concrete Structures, Technische Universität München, Munich, Germany

ABSTRACT

Various types of concrete structures have been strengthened by using externally bonded CFRP strips. For the design of such strengthening projects numerous design standards and guidelines are available. The design approaches of some of these guidelines and standards are mainly based on full-scale tests. These full-scale tests are often carried out on three- or four-point bending tests with continuous reinforcement. By contrast in actual building practice, continuous loads, cut-off reinforcement and continuous girders dominate. It can be theoretically shown that the loading difference and the changing of the reinforcement ratio both have a big influence on the bond force transfer of externally bonded CFRP strips.

In this paper full-scale tests on strengthened reinforced concrete single-span slabs with cut-off reinforcement and full-scales tests on two-span slabs strengthened in the hogging region are presented. Some of these tests were also loaded using a setup which simulates a continuous load approximately. In the tests, either shear failure or bond failure occurred. After the description of the tests the results are compared to the predicted load-carrying capacity of several guidelines. These comparisons show that some guidelines and approaches, which are mainly based on mechanical principles, perform well with the results. By contrast some of the more empirically based guidelines do not predict the failures quite as well.

KEYWORD

CFRP strips, bond performance, full-scale tests, code evaluation
Double Shear Tests for Characterisation of Bond between FRP EBR and Concrete

Andreea Serbescu
PhD Student, Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK

Maurizio Guadagnini
Dr., Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK

Kypros Pilakoutas
Prof., Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK

ABSTRACT

The strengthening potential of FRPExternally Bonded Reinforcement (EBR) is already well established. However, the optimum design of FRP systems cannot yet be achieved due to premature debonding. Despite the large amount of research efforts, existing bond capacity models still lead to either uneconomic or unsafe predictions with large scatter. Valuable input for many models is provided by the interfacial bond-slip relationship determined from various simplified bond tests, especially the double shear test. A Round Robin Test exercise was carried out at 7 international laboratories in order to assess the feasibility of the double shear test as a potential standardised procedure. The present paper describes the methodology followed and reports the findings of the tests performed at The University of Sheffield on 6 different types of EBR systems. The discussion of the results includes the influence of various parameters on the bond-slip development as well as the effect of roughness of the substrate surface on bond capacity. The paper also offers a critical view on the drawbacks and limitations that this type of test can have in reproducing the actual stress state existing in RC beams. Suggestions for further improvements of the testing procedure are also proposed.

KEYWORD

bond stress, EBR, double shear test, concrete surface roughness, interfacial bond law
Interface Bond Strength of Helical Wrapped GFRP Ground Anchors

Weichen Xue
Prof., Department of Building Engineering, Tongji University, Shanghai, China

Yuan Tan
PhD candidate, Department of Building Engineering, Tongji University, Shanghai, China

ABSTRACT

63 pull-out specimens were tested to investigate the interface bond strength between helical wrapped GFRP ground anchors and different bonding agents. Test variables included types of bonding agents (normal concrete (NC) 20, 30 and 50, high performance concrete (HPC) 50, grout and epoxy resins) and types of anchors (helical wrapped GFRP anchor, deformed steel anchor, round GFRP anchor and steel anchor). Experimental results showed interface bond strength of helical wrapped GFRP anchors was 61% to 94% of that of steel anchors in concrete, which mainly depended on bond behavior between the inner cores and spirally wound ribs of GFRP anchors. With concrete strength increased, the interface bond strength of helical wrapped GFRP anchors increased but the trend of increasing slowed down. Compared to helical wrapped GFRP anchors, the interface bond strength of round GFRP anchors was very low which indicated that round GFRP anchors was not suitable for ground anchors in geotechnical engineering. The higher interface bond strength of helical wrapped GFRP anchors in grout and epoxy resin could provide references for the applications of GFRP anchors in post-tensioned bonded prestressed concrete structures and the development of helical wrapped GFRP anchor system.

KEYWORD

ground anchor; helical wrapped GFRP anchor; bonding agents; bond strength; pull-out test
A Study on Flexural Bonding Strength for Embedded Length of FRP Rods

J. Sim
Department of Civil & Environmental Engineering, Hanyang University, Korea

T. Kang
SAMPYO Construction & Engineering Co., Ltd, Korea

J. Park
EJtech Co., Ltd, Korea

H. Kim
Department of Civil & Environmental Engineering, Hanyang University, Korea

H. Lee
Department of Civil & Environmental Engineering, Hanyang University, Korea

ABSTRACT

This study has been conducted to examine bond strength of Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) rebars in concrete beam subjected to 4-point bending test by adopting BRITISH STANDARD that is used to investigate effect of concrete in bonding test. The test variables were made to have bonding length of 15times(15db), 17.5times(17.5db) and 20times(20db) of the nominal diameter of GFRP and CFRP rebar and were done to analyze the relationship between the bonding strength and the slip. The test results showed that, a pattern of the concrete splitting failure appeared in all specimens and the bond strength in case of CFRP rebars (20db) was observed as the least of all values.

KEYWORD

Pull-out test, bond behavior, GFRP, CFRP, bond strength, BRITISH STANDARD
Geometrically Nonlinear Stress Analysis for Imperfect CFRP Reinforced Steel Cylinders under Compression

Krishna Kumar Bhetwal
PhD. Student, Dept of Civil and Arch. Eng., Toyohashi University of Technology, Toyohashi, Japan

Seishi Yamada
Professor, Dept of Civil and Arch. Eng., Toyohashi University of Technology, Toyohashi, Japan

Yukihiro Matsumoto
Asst. Professor, Dept of Civil and Arch. Eng., Toyohashi University of Technology, Toyohashi, Japan

Sreing Sonit
Student, Dept of Civil and Arch. Eng., Toyohashi University of Technology, Toyohashi, Japan

ABSTRACT

Steel cylindrical shells when exposed to the hostile chemical on marine environments show their vulnerability to corrosion. At the same time, it becomes difficult to achieve required level of load carrying capacity by using shells constructed just from fibre reinforced polymer. In this context, carbon fiber reinforced polymer (CFRP) if collectively used with thin steel shells, the physical and chemical properties as a new composite structure will increase tremendously. On our previous study (CICE 2010 in Beijing), it has been predicted that the buckling load carrying capacities of thin cylindrical shells increase with CFRP reinforcement through the linear buckling, the reduced stiffness (RS) and the nonlinear imperfection analyses. The present extensive research study discusses the way of an alternative simple confirmation of elastic nonlinear stress variations near the interface between CFRP and steel layers in any prebuckling equilibrium states.

KEYWORD
Carbon fibre reinforced polymer(CFRP) , Linear buckling analysis, Reduced stiffness analysis (RS analysis), Nonlinear imperfection analysis, Buckling strength, Composite structures, Bond stress, Cylindrical shell
Static and Fatigue Experimental Study on Flexural Behavior of Hybrid GFRP-Concrete Bridge Decks

Yuqing Liu
Prof., Department of Bridge Engineering, Tongji University, Shanghai, China

Haifeng Fan
MSc., Department of Bridge Engineering, Tongji University, Shanghai, China

Jun He
PhD, Department of Bridge Engineering, Tongji University, Shanghai, China

Dingjun Wu
Prof., Department of Bridge Engineering, Tongji University, Shanghai, China

ABSTRACT

A new type of cost-effective hybrid GFRP/Concrete deck system is proposed. It consists of the corrugated pultruded GFRP plate with T-upstands for the tension part and concrete with distributing reinforcing bars for the compression part. In order to study its structural performance under static and cyclic loadings, four-point bending test and fatigue test were conducted on a full-scale specimen, respectively. Results from experimental work indicate that the proposed hybrid bridge deck had expected strength and stiffness, both surface treatment and penetrating bars improve the connection between GFRP plate and concrete, also promote the ultimate strength and whole rigidity of hybrid deck. Furthermore, the deck specimen hardly exhibits any stiffness degradation and slippage of the concrete from the GFRP bottom plate even after 3.1 million cycles that means such hybrid deck had a good fatigue performance.

KEYWORD

Bridge, Hybrid bridge deck, Experimental tests, Glass fiber reinforced polymer, Concrete
Flexural Strength Analysis of CFRP Box Beams
with Different Laminate Structures

Hiroki Sakuraba
Doctoral Student, Graduate School of Engineering, Hokkaido University, Sapporo, Japan

Takashi Matsumoto
Associate Prof., Faculty of Engineering, Hokkaido University, Sapporo, Japan

Toshiro Hayashikawa
Prof., Faculty of Engineering, Hokkaido University, Sapporo, Japan

ABSTRACT

This paper presents an analytical investigation on the flexural strength of CFRP box beams with six different laminate structures. Those six laminates have 25 or 24 laminas, and they have the proportion of longitudinal, transverse, and diagonal laminas (±45°, except for one laminate of ±60°) as 1:1:0 (L1T1), 1:0:2 (L1D2), 1:0:1 (L1D1), 1:1:2 (L1T1D2), 2:0:1 (L2D1), and 1:0:2 (±60°) (QISO60). Two specimens were prepared for L1D1, which are distinguished as L1D1-a and L1D1-b, while one specimen was prepared for other proportions. All the specimens were tested under four point bending. The bending tests showed that QISO60 exhibited the highest strength, followed by L1D1-a, L1D2, L1D1-b, L1T1D2, L2D1, and L1T1. The diagonal laminas seem to be effective to enhance the flexural strength compared to the transverse laminas. However, the flexural strengths exhibited a small difference due to a premature damage which occurred near loading plates.

Finite element analysis is carried out in order to examine the flexural strength. The beams are modeled by thin shell elements with classical lamination theory. Failure of the models is defined by the first ply failure approach. The analysis indicates significantly different flexural strengths from those in the tests, if the premature damage does not happen. Indeed, L2D1 represents the highest flexural strength, followed by L1D1, L1D2, L1T1, L1T1D2, and QISO60. Also, failures in the analysis occur at the same place as in the tests. The effect of the different laminate structures to the flexural strength can be clearly observed.

KEYWORD

CFRP, box beam, laminate structure, flexure, flexural strength
A New Analytical Model for Concrete Cover Separation of R/C Beams Strengthened with FRP Laminates

Dawei Zhang

Postdoctoral fellow, Faculty of Engineering, Hokkaido University, Sapporo, Japan

Tamon Ueda

Prof., Faculty of Engineering, Hokkaido University, Sapporo, Japan

Hitoshi Furuuchi

Assit. Prof., Faculty of Engineering, Hokkaido University, Sapporo, Japan

ABSTRACT

External bonding of fibre reinforced plastic (FRP) laminates to reinforced concrete (RC) beams has been found to be an effective technique for flexural strengthening. The ultimate flexural strength of strengthened RC beams can be improved significantly. However the premature failure modes, such as concrete cover separation, prevent the full flexural capacity from being achieved. The objective of this paper is to establish a simple and accurate design methodology based on the concrete tooth model to predict the load carrying capacity of a FRP laminate strengthened RC beam with concrete cover separation. An analytical expression is developed taking into account the stress concentrations in concrete near the tension rebar closest to the shear crack initiating from cut off point of the FRP laminate. The derivation of the expression involves three major steps: (1) determination of the tensile stress in the FRP laminates assuming a full monolithic action; and (2) obtaining the local stresses and comparison with the concrete strength and (3) prediction of the length of concrete cover separation when the peak load of strengthened beam is reached. The reliability and accuracy of the proposed analytical procedure has been successfully verified by comparing analytical and experimental peak loads of the 52 FRP laminate strengthened beams with concrete cover separation available in the literatures.

KEYWORD

FRP strengthening; debonding; concrete cover separation; concrete tooth model
Fatigue Test on Out-of-Plane Gusset Welded Joints Strengthened with Carbon Fiber Reinforced Polymer Materials

Tao Chen
Assistant Prof., Department of Building Engineering, Tongji University, Shanghai, China

Qian-Qian Yu
Doctoral Student, Department of Building Engineering, Tongji University, Shanghai, China

Xiang-Lin Gu
Prof., Department of Building Engineering, Tongji University, Shanghai, China

Xiao-Ling Zhao
Prof., Department of Civil Engineering, Monash University, Victoria, Australia

ABSTRACT

This paper reports an experimental study on out-of-plane gusset welded joints strengthened with carbon fiber reinforced polymer (CFRP) sheets or plates. Weld toe radius and flank angle were measured with silicon based impression materials before fatigue tension test. Constant amplitude fatigue loadings were applied to 8 specimens with CFRP sheets, 8 specimens with CFRP plates and 5 specimens without reinforcement as the control group. Their fatigue lives and failure modes were observed. All cracks initiated from weld toes on the base plate that are adjacent to longitudinal plate ends. Fatigue lives of all the specimens, which were plotted in S-N graphs, were above the fatigue design F-class curve recommended for steel structures (Japanese Society of Steel Construction). Fatigue life was extended to some extent although scatters were observed in the test results of strengthened specimens. Possible explanations are discussed in the paper and future work is pointed out.

KEYWORD

fatigue test, carbon fibre reinforced polymer, strengthening, out-of-plane gusset welded joint
Design Equations for Shear Capacity of Concrete Girders Strengthened in Shear with Externally Bonded FRP Sheets

Abdeldjelil Belarbi
Professor and Chair, Department of Civil and Environmental Engineering, University of Houston, Texas, USA

Daniel Kuchma
Associate Professor, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Illinois, USA

Ayman Okeil
Associate Professor, Department of Civil and Environmental Engineering, Louisiana State University, Louisiana, USA

Sang-Wook Bae
Assistant Professor, Department of Department of Civil and Environmental Engineering, Texas Tech University, Texas, USA

ABSTRACT

External strengthening with FRP is generally used for flexural strengthening, confinement, and improvement of ductility in columns or shear strengthening. While flexure is typically the limiting mode of failure in bridge girder design, shear failure may dominate in cases where the original transverse reinforcement has been severely corroded or the flexural strength has increased due to flexural strengthening. In such cases, the shear capacity should be enhanced to preclude shear failures which can be catastrophic. Though there has been a significant amount of research conducted on flexural and axial strengthening, the use of externally bonded FRP for shear strengthening has not been investigated as extensively. Despite limited experimental research, many models have been proposed for predicting the shear contribution of externally bonded FRP. These models are diverse in their approach and, in many cases, contradictory in their estimates of strength increase.

This study was conducted as part of NCHRP 12-75 project to develop design equations and provisions. To achieve the goal of this study, a total of 49 published experimental studies containing more than 500 test results were reviewed and compiled into a database format. With this database, not only the performance of existing analytical models and design equations were evaluated, but also the parameters affecting the shear behavior of concrete girders strengthened in shear with FRP were identified. Finally, new and improved design equations were proposed in this study, and a reliability analysis was performed on the proposed design equations, using procedures similar to those in the calibration of AASHTO LRFD Bridge Design Specifications. The reliability analysis showed that the reliability indexes of the proposed design equations are nearly the same for all girder spacing and is about 3.5 for shorter span lengths but decreases for longer spans.

KEYWORD

shear, T-beam, FRP, strengthening, design equations
Performance Evaluation of Different Anchorage Systems for Externally Bonded FRP Sheets for Shear Strengthening of Concrete Structures

Abdeldjelil Belarbi
Professor and Chair, Department of Civil and Environmental Engineering, University of Houston, Texas, USA

Carlos Ortega
Graduate Research Assistant, Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Missouri, USA

Sang-Wook Bae
Assistant Professor, Department of Civil and Environmental Engineering, Texas Tech University, Texas, USA

ABSTRACT

Externally bonded fiber reinforced polymer (FRP) composites have been used to increase shear strength of concrete structures. To increase the effectiveness of the strengthening with externally bonded FRP, the premature failure due to FRP debonding should be avoided. As a result, efforts to prevent debonding have led to the investigation of many different kinds of anchorage systems. An effective anchorage system allows externally bonded FRP reinforcements to continue carrying a load even after debonding occurs.

In the present study, three different anchorage techniques were investigated for their ability to delay or prevent the debonding failure mode through an experimental program on eight full-scale reinforced concrete T-beams. These systems were (1) discontinuous mechanical anchorage (DMA system), sandwich panel mechanical anchorage (SDMA system), and additional horizontal FRP strips (HS system). The DMA system consisted of two hybrid FRP plates bonded together with epoxy then anchored firmly in place with epoxy and concrete wedge anchors. The SDMA system consisted of a modification to the DMA system in which the ends of vertical FRP strips are wrapped around the first FRP plate and overlapped with a second FRP plate. The HS system was the simplest of the three anchorage systems in which additional horizontal FRP sheets were applied continuously along the test region at the critical bond locations (i.e., at the end of vertical FRP strips).

Results indicated that the SDMA system performed best followed by the DMA and HS systems. In addition, it was found that interaction between the external FRP strengthening and stirrups exists, and furthermore, the use of a mechanical anchorage system affected the level of shear contribution of stirrups. This must be investigated in more detail and integrated into the design of externally bonded FRP shear strengthening.

KEYWORD

bond, anchorage, FRP, shear strengthening