FRP INTERNATIONAL

the official newsletter of the International Institute for FRP in Construction

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Messages

Message from the New Editor

Professor Peng Feng, Tsinghua University, China.

I feel truly honoured to have been appointed as the editor of FRP International. FRP International is now in its 15th year since it became the official newsletter of the International Institute for FRP in Construction (IIFC) in 2004.

Thanks to the former editors Vistasp Karbhari, Rudolf Seracino, Kent Harries, and Tao Yu, FRP International has now become an important forum for items of interest to the IIFC community, reporting important events, research advances, case studies and field applications among other things.

I would like to take this opportunity to reiterate the plea of my predecessors to all IIFC members: Please become an FRP International author. The newsletter will only be as useful and interesting as you help to make it. I look forward to serving IIFC and working with the entire IIFC community.

Message from the New President

Professor Scott Smith, Southern Cross University, Australia.

Dear Colleague:

Welcome to this final instalment of *FRP International* for 2018. Central to this issue is an account of the IIFC flagship conference, CICE 2018, which was held in Paris this year. The conference Chairs Professor Emmanuel Ferrier, Dr Karim Benzarti and Dr Jean-François Caron, and their team, are to be congratulated on running an exemplary conference.

At CICE 2018, a new Executive Committee was elected that will serve IIFC for the 2018-2020 term. The members of the new committee are identified in this newsletter, as well as the IIFC website (www.iifc.org). It is my singular honour to be elected the fifth President of IIFC in this fifteenth anniversary year of the institution. I look forward to working with the Executive Committee, the Advisory Committee, the Council as well as the wider IIFC membership as we continue to advance the institute and the application of FRP composite in the built environment around the world. Also elected at CICE 2018 were five new IIFC Fellows and 15 members of Council. Congratulations on their outstanding achievements.

I would like to take this opportunity to sincerely thank the outgoing Executive Committee under the leadership of Professor Jian-Fei Chen. It has been an absolute pleasure to work with Professor Chen in my previous role as Senior Vice President, and I thank him on behalf of IIFC for his dedicated and enthusiastic leadership for these past four years. Professor Chen will now serve IIFC as a member of the Advisory Committee, as is the convention for past presidents. I would also like to take this opportunity to thank our Advisory Committee members, Honours Committee members and Council members who have completed their terms.

IIFC is a vibrant organisation and its approximately 700 membership is positively impacting the research, manufacture and application of FRP composites in construction around the world. The organisation, however, needs to remain cognisant of world trends and demands. In light of this backdrop, I urge all members and friends of the institute to become involved. You can contribute in multiple ways. Please share with us your research, projects and new FRP materials stories through the institute's internationally-distributed newsletter, *FRP International*. Articles can be directed to the Newsletter Editor, Professor Peng Feng (fengpeng@tsinghua.edu.cn). Please also share with us your ideas about the institute as well as the wider FRP composites in construction field. Feel free to contact directly myself, the IIFC Secretary, or any other member of the Executive Committee.

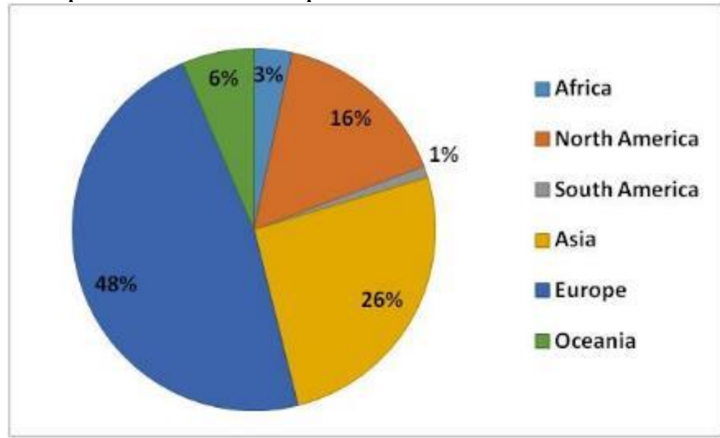
Events

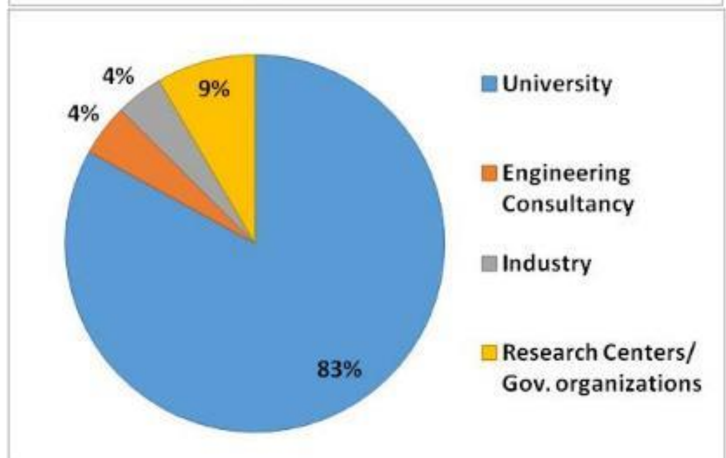
Report from CICE 2018

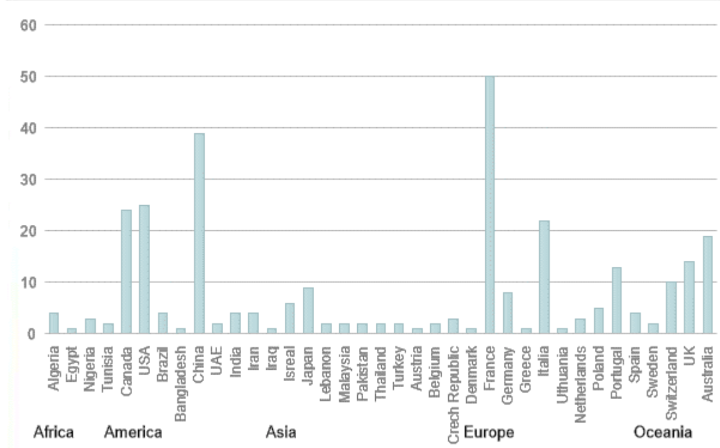
The 9th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2018)

The 9th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2018) was held in Paris, France on 17-19 July 2018. Since its launch in 2001 in Hong Kong, the CICE conference series has travelled to Adelaide (2004), Miami (2006), Zurich (2008), Beijing (2010), Rome (2012), Vancouver (2014) and Hong Kong (2016). **The conference is the official conference series of the International Institute for FRP in Construction (IIFC).**The conference was jointly hosted by the French institute of science and technology for transport, development and transport (IFSTTAR), Ecole des Ponts ParisTech and the University Claude Bernard LYON 1. Following the well-established tradition of the series, CICE 2018 have provided an international forum where engineers, researchers, and practitioners in the field of FRP composites in civil engineering can exchange and share recent advances and future perspectives.

The conference attracted 296 participants from 37 countries and the conference program comprised about 256 presentations.







On behalf of the Organizing Committee, we would like to once again thank all authors for their careful preparation of manuscripts, all Keynote and Invited Speakers for sharing their work and insight at the conference, and all special session organizers for mobilization researchers in their specialized areas to attend this conference. We would also like to thank the IIFC who organized the selection of papers for the IIFC Best Paper Awards.

Technical Program

The technical program consisted of six keynote lectures and special sessions in addition to

251 presentations. The keynote speakers were from different continents of the world and their presentations covered a wide range of topics.

The six keynote presentations, in the order of presentation at the conference, are as follows:

- **Tao Yu**, University of Wollongong Hybrid FRP-Concrete-Steel Tubular Members
- **Lawrence C. Bank**, City University of New York Opportunities for Recycling and Reuse of FRP Composites for Construction in a Circular Economy
- **Jian-Guo Dai**, Professor, The Hong Kong Polytechnic University, Hong Kong, China Structural Behavior of FRP-Reinforced Geopolymer Concrete Sandwich Wall Panels for Prefabricated Construction
- **Neil Farmer**, BSc CEng FICE, Executive Director Tony Gee and Partners, Development of UK Design Guidance for FRP Bridges
- **Brahim Benmokrane**, Professor, University of Sherbrooke, Recent Developments on FRP Rebars as Internal Reinforcement in Concrete Structures and Field Applications
- **Samuel Durand**, Senior Structural Engineer & Manager, MECA, Composite material in architecture : applications, regulations and future challenge

In addition to the above keynote presentations, 37 sessions for both special sessions and free submissions covering the following topics were held:bond behavior, confinement, strengthening of structures with FRP composites, fibre reinforced cementitious matrix (FRCM) for strengthening and new construction, FRP composites in new construction, FRP steel strengthening, performance under seismic and severe loadings, performance in severe environments, masonry, and field applications.

Very fruitful exchanges and discussions occurred during Q&A sessions, coffee breaks and lunch breaks.

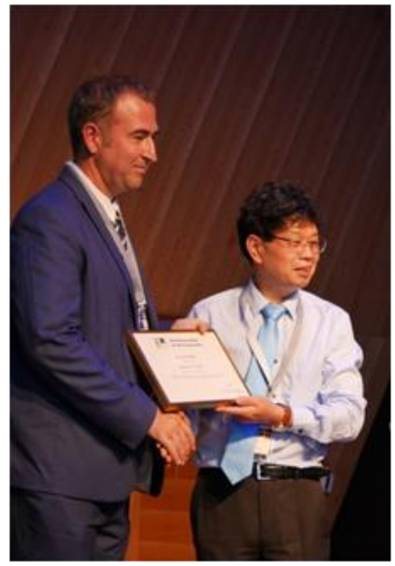
Welcome reception at Tour Eiffel

During the first day of the conference a welcome reception was organized at The Gustave Eifel Salon in the Tour Eifel Tower. Guests have the pleasure to enjoy the salon until late with open discussion with new and old FRP's friends.

The IIFC Medal**,** Distinguished Young Researcher Award and President Award were given to Brahim Benmokranne, Tao Yu and Emmanuel Ferrier during this welcome reception.

IIFC Medal –Brahim Benmokranne

Distinguished Young Researcher Award- Tao Yu



President Award- Emmanuel Ferrier

IIFC meetings

During the conference, IIFC also held its general meeting to discuss about IIFC. In addition, the Council meeting as well as the combined Advisory Committee and Executive Committee meeting were held during the conference.

Closing Ceremony and Awards

Prof. Raafat El-Hacha chaired the closing ceremony. Prof. Scott Smith presented the best thesis award certificates to the Award Winners.

The Best Paper Awards were given at CICE 2018, selected from a total of around 256 papers by the Best Paper Awards Committee for CICE 2018 which is composed of Prof. Scott Smith (Chair), Prof. Jian-Guo Dai and Dr. João Correia. The CICE 2018 BEST PAPER Award for Research on FRP Strengthening of Existing Structures was awarded to E. Ghafoori, A. Hosseini, E. Pellissier, M. Hueppi and M. Motavalli for the paper entitled "Application Of Pre-Stressed Un-Bonded CFRP for Strengthening of Metallic Structures". The CICE 2018 BEST PAPER Award for Reporting Use of FRP in New Construction was awarded to N. Grace, M. Chynoweth, T. Enomoto and M. Bebawy for the paper entitled "I-75 Bridge Over Sexton/Kilfoil Drain, The Longest Highway Bridege Span Prestressed With CFRP Strands".

During the closing ceremony the winners of the Best Photos Award was announced, including the photos coming from the jury of expert and the photos selected by the public vote during the conference.

The rhythm

Vu Linh

Tokyo Metropolitan University

(Jury Choice and Public Vote)

Crack opening

Aida Cameselle-Molares

École Polytechnique Lausanne

(Jury Choice and Public Vote)

Bridge to FRP
Liu Xing
Tsinghua University
(Jury Choice)

CFRP Strengthening
Elyas Ghafoori
Swiss Federal Laboratories (Empa)
(Public Vote)

At the end of the closing ceremony, the Chair and Co-Chair of the local Organizing Committee were each presented by the IIFC president with a certificate of appreciation from IIFC for their work for CICE 2018. Prof. Raafat El-Hacha chaired the closing ceremony.

Acknowledgement

To conclude this report, we would like to thank many people for their contributions to the organization of CICE 2018; in particular, we are indebted to all members of the International Organizing Committee and International Scientific Committee.

Invitation to Upcoming Events

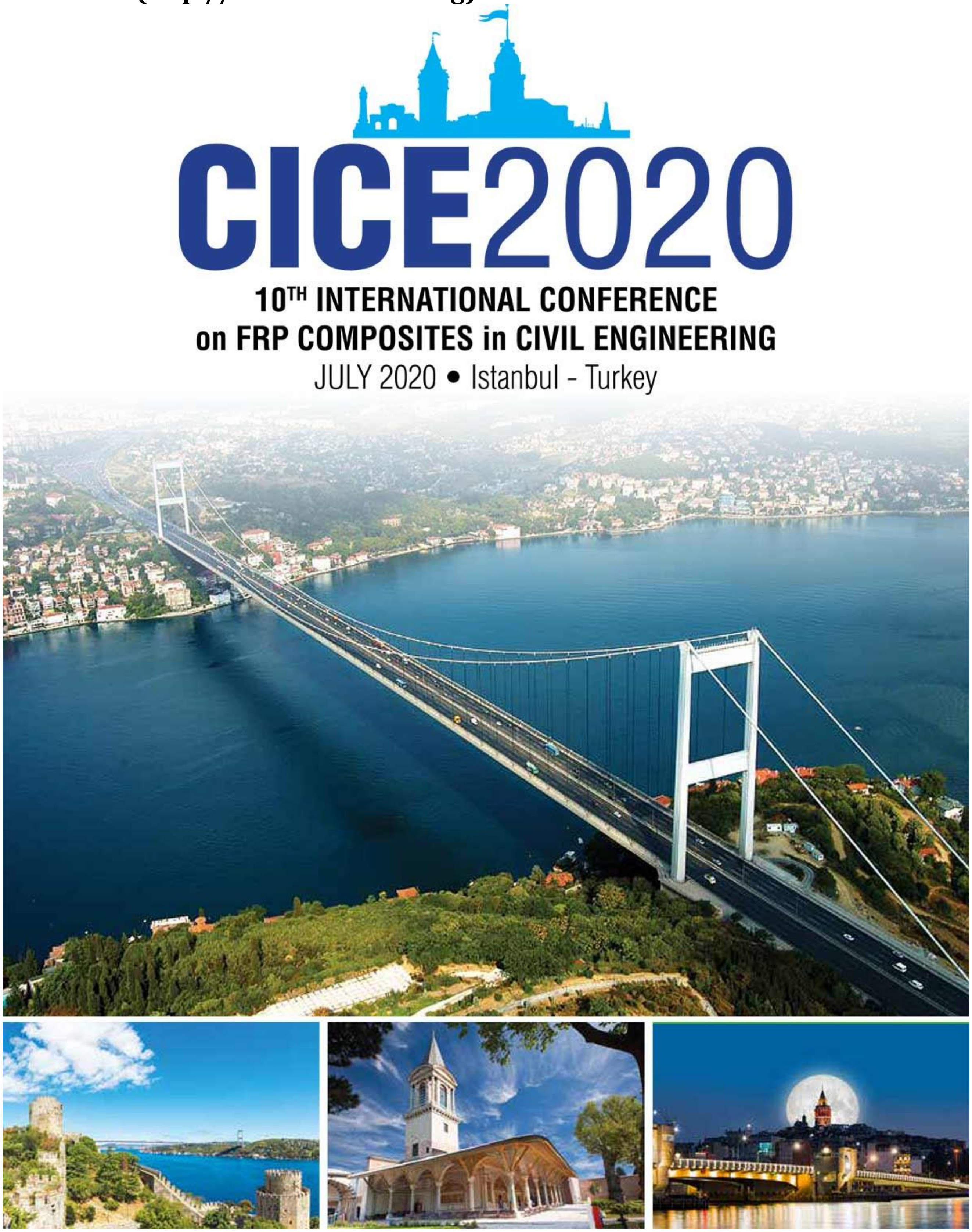
FRPRCS-14 (http://www.qub.ac.uk/sites/FRPRCS-14/)

The 14th International Symposium on Fiber-Reinforced Polymer Reinforcement of Concrete Structures (FRPRCS) will be held in Queens University Belfast.

This international symposium attracts interest from researchers, practitioners, and manufacturers involved in the use of fiber-reinforced polymers (FRPs) as reinforcement for concrete masonry structures. This includes the use of FRP reinforcement in new construction and FRP for strengthening and rehabilitation of existing structures.

The papers will not only emphasize the experimental, analytical, and numerical validations of using FRP composites but will also be aimed at providing insights needed for improving existing guidelines. New frontiers of FRP research will be explored that provide information on emerging materials, systems, and applications for extreme events such as fire and earthquakes. The technical papers will also feature discussions on sustainability, novel applications, new technologies, and long-term field data that will result in greater acceptance and use of FRP composites technology by practitioners.

CICE 2020 (http://www.cice2020.org)



The IABSE Symposium Guimarães 2019(www.iabse.org/guimaraes2019)

GUIMARÃES IABSE SYMPOSIUM 2019 | 27 - 29 MARCH 2019

The IABSE Symposium Guimarães 2019 'Towards a Resilient Built Environment - Risk and Asset Management' will be held on March 27-29, 2019, at Vila Flor Cultural Centre.
Focus will be given to cutting-edge issues, such as Novel Management Tools for the Built Environment, Lifecycle Quality Control of New and Existing Infrastructures, and Advanced Frameworks for a Sustainable Built Environment and Risk Analysis Procedures.

Keynote Sessions will be given by renowned experts of each theme of the Symposium and will address the most innovative findings of their ongoing work.

Special Sessions will grant the opportunity to present developments related to a specific topic proposed by highly respected individuals on that field of research or technical practice. Each contribution to these sessions consists of a paper of six to eight pages and an oral presentation followed by an open floor discussion for the audience to participate in.

Scientific and Technical Sessions will consist of the presentations, as well as lessons learned and future prospects. Each contribution to these sessions consists of a paper of six to eight pages and a presentation.

Objectives

- Place the topic of Sustainability of the Built Environment in an International Discussion Forum.
- Offer a worldwide discussion in risk assessment and infrastructure asset management with an exchange of knowledge from different stakeholders.
- Discuss Performance and Costs of built environment assets, with a focus on "Zero Maintenance".
- Provide the adaptation of Young Engineers to the topics of Risk, Construction, Quality, Resilience and Management.

IIFC Business Conducted at CICE 2018

IIFC General Meeting

The IIFC General Meeting was held on July 17, 2018 at CICE 2018. Five IIFC members were elected as IIFC Fellow at CICE 2018. Fifteen members were elected and/or re-elected to the IIFC Council and their profiles are presented in the following pages.

IIFC Council Meeting

Following the General Meeting in Paris, the Council met to elect the IIFC Executive Committee that will steer IIFC through CICE 2020. The new roster is presented on the following pages.

IIFC President Prof. Jian-Fei Chen (Queen's University Belfast, UK), Conference coordinator Prof. Gui Jun Xian (Harbin Institute of Technology, China), members-at-Large Dr. Dilum Fernando (University of Queensland, Australia) and Takashi Matsumoto (Hokkaido University，Japan) completed their terms on the Executive Committee and were recognized for their service and contributions.

Prof. Scott Smith (Southern Cross University, Australia) replaces Prof. Jian-Fei Chen (Queen's University Belfast, UK) as IIFC President.

Prof. Amir. FAM (Queen's University, Canada) replaces Prof. Scott Smith (Southern Cross University, Australia) as IIFC senior Vice President.

Dr. Kent A. Harries (University of Pittsburgh, USA) and Dr. Jian-Guo Dai (Hong Kong Polytechnic University, China) and Prof. E. Ferrier (University Lyon I, France) remain on the Executive Committee as the IIFC Vice President.

Prof. Peng Feng (Tsinghua University, China) replaces Dr. Tao Yu (University of Wollongong, Australia) as the newsletter editor.

Dr. Tao Yu, Prof. Raafat. EL-HACHA (University of Calgary, Canada) and João R. Correia (University of Lisbon, Portugal) remain on the Executive Committee as the IIFC Secretary, the IIFC Treasurer and the IIFC Webmaster separately.

Dr. Lijuan. Cheng(University of California, Davis, USA) , Prof. Shi Shun Zhang, Huazhong University of Science and Technology, China) , Rebecca Gravina(RMIT University, Australia), Carlo Paulotto (ACCIONA Infraestructuras S.A. Spain), Karim Benzarti(France Université Paris-Est, France) join as members at large.

Su E. Taylor (Queen's University Belfast, Ireland) joins the Executive Committee as the Conference coordinator for FRPRCS-14 2019 and Alper Ilki (Istanbul Technical University, Turkey) is the Conference coordinator for CICE 2020.

IIFC Fellow Elected at CICE 2018

John Myers
USA

Issam Harik
USA

Luke Bisby
UK

Jian-Guo Dai
China

Peng Feng
China

IIFC Council Members Elected at CICE 2018

T. OZBAKKALOGLU, University of Hertfordshire, UK

R. GRAVINA, RMIT University, Australia

S. SHEIKH, University of Toronto， Canada

R. Li, Central Research Institute of Building and Construction Co., Ltd of MCC, China

K. BENZARTI, Université Paris-Est， France

I. YOSHITAKE, Yamaguchi University, Japan

J.R. CORREIA University of Lisbon, Portugal

C. PAULOTTO, ACCIONA Infraestructuras S.A. Spain

E. GHAFOORI, Empa - Swiss Federal Laboratories for Materials Science and Technology, Switzerland

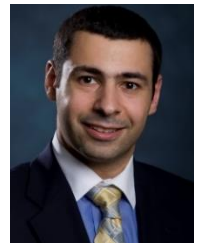
L.J. CHENG, University of California, Davis, USA

J. J. MYERS, Missouri University of Science and Technology, USA

J.G. DAI, The Hong Kong Polytechnic University, China

J. SCHMIDT, Technical University of Denmark, Denmark

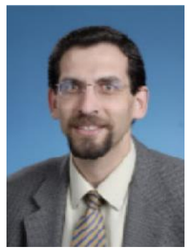
N. GRACE, Lawrence Technological University, USA



M. DAWOOD, University of Houston , USA

2018-2020 IIFC Executive Committee

President
S. SMITH, Southern Cross University, Australia



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Vice President
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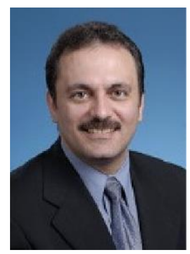
Vice President
J.G. DAI, The Hong Kong Polytechnic University, China

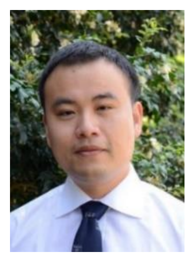
Vice President
E. FERRIER, University Lyon I, France



Treasurer
R. EL-HACHA, University of Calgary, Canada

Newsletter Editor
P. FENG, Tsinghua University, China

Webmaster
J.R. CORREIA, University of Lisbon, Portugal



Secretary
T. YU, University of Wollongong, Australia

Conference coordinator
S.E. TAYLOR (FRPRCS-14 2019) Queen's University Belfast, Ireland

Conference coordinator
A. ILKI (CICE 2020) Istanbul Technical University, Turkey

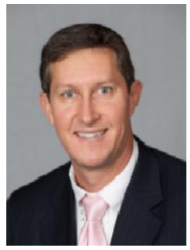
Member-at-Large
L.J. CHENG, University of California, Davis, USA

Member-at-Large
S.S. ZHANG,
Huazhong University of Science and Technology, China

Member-at-Large
R. GRAVINA,
RMIT University, Australia

Member-at-Large
C. PAULOTTO,
ACCIONA Infraestructuras S.A., Spain

Member-at-Large
K. BENZARTI,
Université Paris-Est, France



Member-at-Large
D. GREMEL,
Hughes Brothers Inc., USA

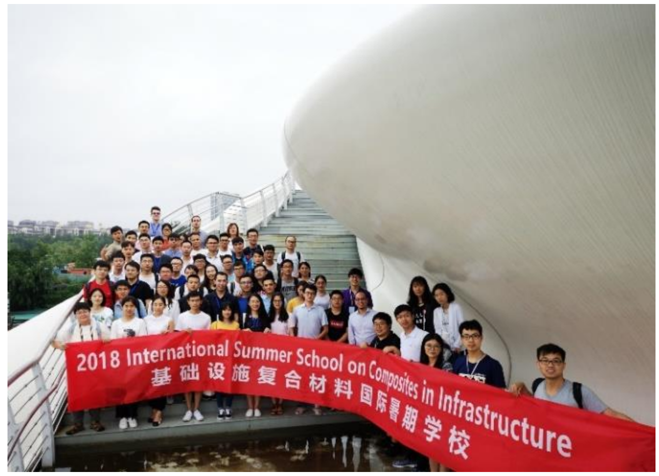
Report from ISSCI 2018

International Summer School on Composites in Infrastructure (ISSCI 2018) was hosted by the International Centre for Composites in Infrastructure (ICCI) at Tsinghua University, Beijing, China on July 9-11, 2018.

ISSCI 2018 invited the world's top scholars to give lectures, including: Prof. Jin-Guang Teng from The Hong Kong Polytechnic University, Prof. Zhishen Wu from Southeast University, Prof. Jian-Fei Chen from Queen's University of Belfast, Prof. Scott Smith from Southern Cross University, Prof. Jian-Guo Dai from Hong Kong Polytechnic University, Dr. Fabio Matta from University of South Carolina, Prof. João R. Correia from the University of Lisbon, Prof. Tao Yu from the University of Wollongong, Prof. Yu Bai from Monash University, Prof. Peng Feng from Tsinghua University.

124 scholars and postgraduates from universities, research institutions and enterprises at home and abroad participated in this summer school. The three-day summer school arranged 16 lectures and one field visit to composite materials engineering. The lectures focused on the application of fiber-reinforced polymers in infrastructure structures. On the basis of their basic mechanics,

the behaviour, modelling and design of composite structures were comprehensively and thoroughly explained. Topics covered the basic mechanics of composite materials, reinforcing structures by composite material and the application of composite materials in new buildings.



Report from ISERCI 2018

International Symposium for Emerging Researchers in Composites for Infrastructure (ISERCI 2018) was held in Beijing and was hosted by the Department of Civil Engineering at Tsinghua University on July 12-14, 2018. The seminar is mainly for young students in the field of civil engineering composite structures and young scholars who have received doctorates within 2015.

Prof. Jian-Fei Chen from Queen's University of Belfast, Prof. Zhishen Wu from Southeast University, Prof. Scott Smith from Southern Cross University, Prof. Weichen Xue from Tongji University, were invited to give keynote speech.

Dr. Fabio Matta from University of South Carolina, Prof. João R. Correia from the University of Lisbon, Prof. Tao Yu from the University of Wollongong and Prof. Yu Bai from Monash University, as outstanding representatives of young scholars, also gave keynote speech to the conference.

ISERCI 2018 aimed to provide a platform for young scholars and new research stars in this field to share the latest research. More than 80 scholars from universities and research institutions at home and abroad participated in ISERCI 2018. The presentations covers: FRP-confined concrete, pultruded FRP, pre-stressed CFRP laminates and etc.

Publications

Best Papers of CICE 2018

APPLICATION OF PRE-STRESSED UN-BONDED CFRP FOR STRENGTHENING OF METALLIC STRUCTURES

E. Ghafoori [1,2], A. Hosseini [1, 3], E. Pellissier [4], M. Hueppi [4], M. Motavalli [1, 5]

[1] *Empa, Swiss Federal Laboratories for Material Science and Technology, Dübendorf, Switzerland (corresponding author: elyas.ghafoori@empa.ch);*

[2] *Smart Structures Laboratory, Swinburne University of Technology, Hawthorn VIC 3122, Melbourne, Australia*

[3] *Resilient Steel Structures Laboratory, EPFL, Swiss Federal Institute of Technology Lausanne, Switzerland*

[4] *S&P Clever Reinforcement Company AG, Switzerland;*

[5] *University of Tehran, Tehran, Iran*

ABSTRACT

Application of carbon fiber-reinforced polymer (CFRP) composites for retrofitting reinforced concrete structures has been extensively investigated and used in practice. Many studies demonstrated the beneficial influence of such composite materials for the flexural and shear strengthening of concrete girders, as well as for confinement of concrete columns. However, the strengthening techniques and the accompanying theories for metallic structures have not been developed as thoroughly as those for concrete structures. There are several differences between the behavior of bonded joints in CFRP-strengthened concrete and metallic members, which will be briefly explained in this paper. Furthermore, one of the main aims of the paper is to give an overview on different techniques for carbon-fibre reinforced polymer (CFRP) strengthening of steel plates and

beams. Different bonded and un-bonded retrofit systems will be discussed with particular focus on application of pre-stressed un-bonded retrofit (PUR) systems. Furthermore, some details about design and testing procedure of a new so called flat PUR (FPUR) system will be given. Finally, the paper gives some details about CFRP strengthening and wireless sensor monitoring of two old metallic bridges in Switzerland and Australia.

KEYWORDS

Carbon Fiber-reinforced Polymer (CFRP), Steel strengthening, Fatigue, Prestressing, Bonded, Pre-stressed Un-bonded Reinforcement.

INTRODUCTION

Application of carbon fiber-reinforced polymer (CFRP) composites for retrofitting reinforced concrete structures has been extensively investigated and used in practice. Many studies demonstrated the beneficial influence of such composite strips for the flexural and shear strengthening of concrete girders, as well as for confinement of concrete columns. However, the required theories and strengthening techniques for steel structures have not been developed as thoroughly as those for concrete structures (e.g. Ghafoori and Motavalli 2015b & c & a). There are several differences between the behavior of bonded joints in CFRP-strengthened concrete and metallic members, which will be briefly explained in this section.

Key differences between strengthening of steel and concrete structures

Failure mode: The main difference between CFRP–steel and CFRP–concrete bonded joints is that in the former, failure will likely occur in the adhesive layer and in the latter failure is expected to occur in the concrete substrate, proving proper surface preparation. Therefore, by providing an adequate bond length, the optimal bond strength is dependent on the fracture energy of the adhesive for the former and the fracture energy of the concrete substrate for the latter. In the FRP-strengthened steel structures, interfacial failure should happen within the adhesive layer in the form of cohesion failure to maximize the effectiveness of FRP strengthening and minimize variations of the interfacial bond capacity as a result of different surface preparations. Furthermore, it has been observed that the inappropriate surface preparation of the steel substrate prior to the bond application will result in an adhesion failure at the steel-to-adhesive interface (Fernando 2010). Assuming the adhesive as the weakest point of a CFRP-steel bond joint, Ghafoori and Motavalli 2016a have developed a prestressed unbonded reinforcement (PUR) system that can be used as an alternative to the bonded CFRP reinforcement. The developed PUR system functions without using an adhesive layer, hence the performance of the system is no longer dependent on the fracture energy of the adhesive. Strengthening using the PUR system is recommended for cases when the surface of the structure, which has to be retrofitted, is not smooth enough to be bonded to CFRP plates, or when there is a concern about the effects of high ambient temperatures, moisture, freeze/thaw cycles or fatigue behavior of the bonded CFRP-to-metal joint.

Stiffness and deformations: Recent experimental and numerical studies at Empa (Ghafoori and Motavalli 2015b & c) have shown that strengthening of steel beams with pre-stressed CFRP strips does not increase the stiffness of the retrofitted member significantly. This finding is in contrast to retrofitted concrete beams, in which the flexural and/or flexural-shear cracks are often initiated at even service load levels. In the latter case, applying pre-stressed laminates to the tension face of the member can close the existing cracks more efficiently than non-pre-stressed laminates, and thereby, the depth of the compression zone in the concrete beam is increased, which results in an increased stiffness. For the same reason, i.e. increasing the effective depth of the cross-section, utilizing pre-stressed laminates can increase the stiffness of the cracked steel members. Therefore, one of the main difference between the behavior of the CFRP bonded concrete and steel beams is that in the former the cracks are initiated at relatively low load levels in the tension face of the concrete beams, and the bonded CFRP laminate tends to keep the cracks close. However, in the latter, no crack initiates in the steel even after yielding, and the role of an adhesive layer between the CFRP laminate and the steel substrate is limited to transferring the shear stresses from the steel substrate to the CFRP laminate along the connection.

DIFFERENT CFRP RETROFITS SYSTEMS FOR STEEL STRUCTURES

Strengthening steel structures using pre-stressed bonded CFRP composites

Ghafoori and Motavalli 2015c have used bonded non-prestressed normal modulus (NM), high modulus (HM) and ultra-high modulus (UHM) CFRP strips for flexural strengthening of steel beams. It has been shown that UHM CFRP strips are effective in increasing the stiffness of the metallic girders and reducing the flexural deformations. Metallic members have been traditionally strengthened using non-pre-stressed CFRP plates. However, in non-pre-stressed retrofit systems, the dead loads are not transferred to the CFRP plates and only a portion of the live load is transferred to the CFRP plates. As an alternative, by using pre-stressed CFRP plates, a portion of the dead load is transferred to the CFRP plates in addition to the live load (Ghafoori 2013, Ghafoori and Motavalli 2013). It has been shown that prestressed CFRP strips can increase the flexural yield and ultimate load capacity of steel beams substantially. Ghafoori and Motavalli 2015b have shown that prestressed CFRP strips can be used for strengthening of steel beams that are prone to lateral-torsional buckling (LTB) to increase the LTB capacity. Moreover, Ghafoori et al. 2012b studied the performance of notched steel beams retrofitted with CFRP patches under high-cycle fatigue loading regime. The test results for a four-point bending test scheme with a cyclic loading frequency of 4.2 Hz showed that the application of CFRP reinforcements extended the fatigue life substantially, and in some cases, a complete fatigue crack arrest was achieved.

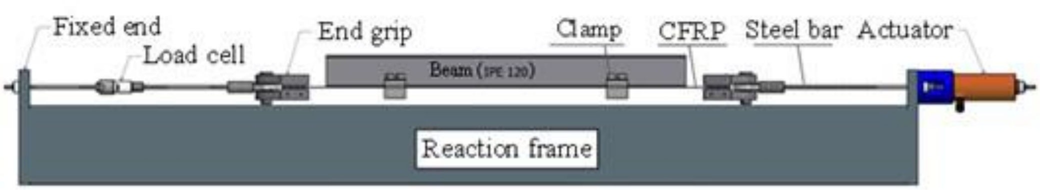
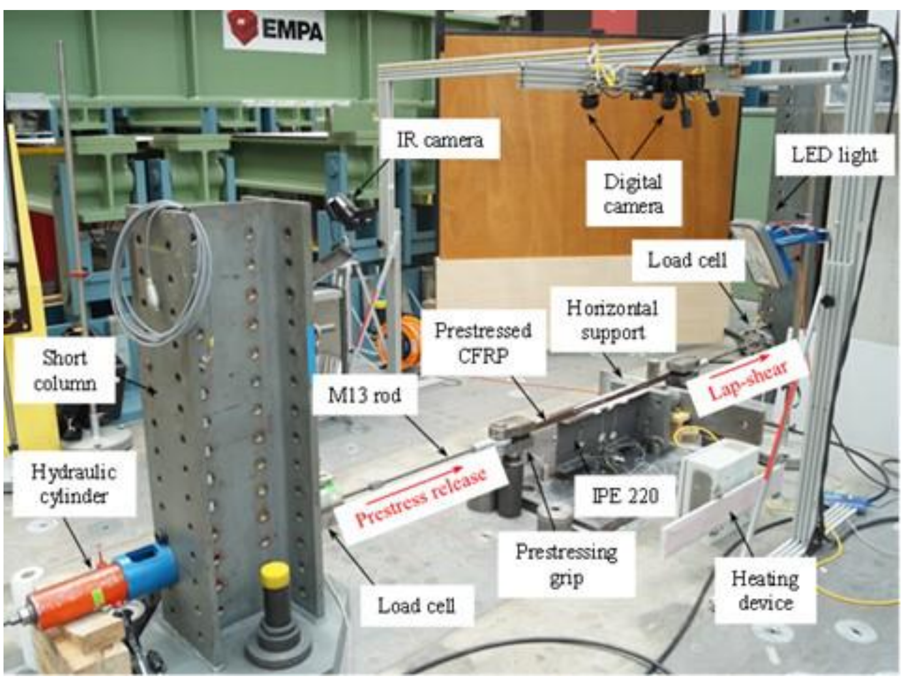
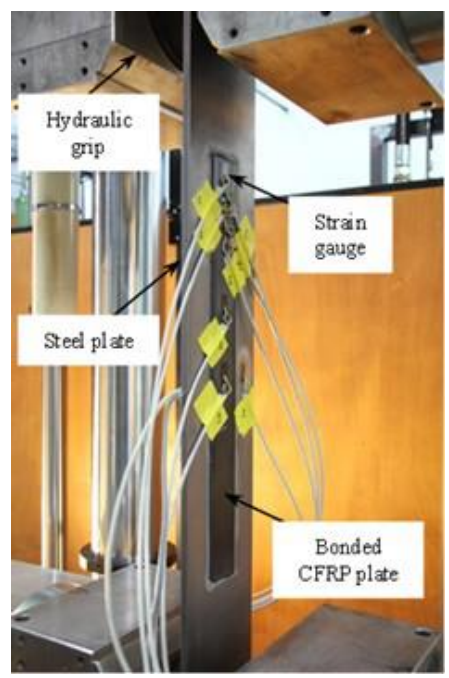


Figure 1. Elements of the pre-stressing set-up, which uses an independent reaction frame to pull the CFRP strip (Ghafoori and Motavalli 2015b).

Through an ongoing research topic at the Structural Engineering Research Laboratory of Empa, a setup for lap-shear and prestress release tests has been developed (see Figure 2a) to investigate the bond behavior of non-prestressed and prestressed CFRP plates to the steel substrate. The designed test setup allows lap-shear and prestress release tests to be systematically performed, while the test be monitored using a 3D digital image correlation (DIC) system. Based on the experimental results and 3D DIC measurements, performed on a set of lap-shear and prestress release tests using the aforementioned setup, it has been demonstrated that accelerated curing of the epoxy adhesive by heating, as an alternative to the conventional cold curing, leads to the same lap-shear strength as room-temperature cured CFRP-to-steel joints. Furthermore, in room-temperature cured joints, the debonding load of prestress release tests is slightly lower than that of lap-shear tests, because of the mixed-mode (I/II) state of the stresses within the bond in a prestress release test (Hosseini et al. 2017b).



(a)



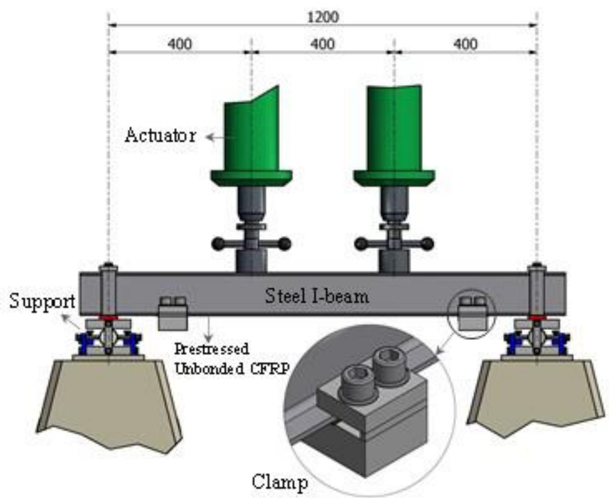
(b)

Figure 2. (a) Lap-shear and prestress release test setup developed at Empa (Hosseini et al. 2017b). (b) Bonded CFRP-strengthened steel plate under uniaxial tensile loading (Hosseini et al. 2016).

It is known that although the existing knowledge on the bond behaviour of CFRP-to-steel obtained through lap-shear tests is crucial to realize the load transfer mechanism; the available models cannot be directly used for the strengthening of steel tensile members using prestressed CFRP plates. Thus, the bond behaviour of non-prestressed and prestressed CFRP plates to the steel substrate has been also studied using CFRP-strengthened steel plates under uniaxial tensile loading (See Figure 2b). An analytical model was developed by Hosseini et al. (2016) to predict the strain in steel and CFRP plates, which its predictions found to be in a good correlation with the performed experiments on CFRP-strengthened steel plates under uniaxial tension. Both the results of the analytical modelling and experimental tests revealed that neglecting the eccentricity in single-side CFRP-reinforced steel members, leads to an unsafe prediction of the stress levels in steel (Hosseini et al. 2017a).

Strengthening steel structures with prestressed unbonded CFRP composites

The majority of the existing research on CFRP strengthening of metallic members has used CFRP materials bonded to the steel substrate. As it has been discussed before, the efficiency of the bonded retrofit system is mainly dependent on the behavior of the CFRP-to-steel bond joint, while the bond strength is limited due to the premature debonding failure. Sophisticated surface preparation is required prior to bonding the CFRP to the steel member to maximize the efficiency of the composite system and reduce the risk of interface debonding.



(a)

(b)

Figure 3. a) Test set-up (all dimensions in mm), b) components of the mechanical anchorage system (Ghafoori and Motavalli 2015b).

Many studies have raised concerns about the influence of environmental conditions (e.g., elevated or subzero temperatures, water and moisture and ultraviolet light) and dynamic loads (e.g., fatigue, impacts and earthquakes) on the behavior of the CFRP-to-steel bond joint. Because of these concerns, which are mainly associated with the long-term performance of the CFRP-to-steel bond joints, a pre-stressed un-bonded retrofit (PUR) system has been recently designed and tested at Empa (Ghafoori and Motavalli 2015b & c & a). In contrast to the pre-stressed bonded reinforcement (PBR) systems, the PUR system works without relying on the bond; instead, it uses a pair of friction-clamps to hold the prestressed CFRP plates to the steel member. An independent reaction frame to pull the CFRP strips was developed, as shown in Figure 1. The pre-stressed CFRP strip was then attached to the steel beam using mechanical clamps. The force in the actuator was then released and the extra CFRP strip, out of the mechanical clamps, was cut.

The retrofitted beams were tested in a four-point bending static loading test set-up, as shown in Figure 3a. Figure 3b depicts the elements of the mechanical anchorage system. It has been shown that prestressed unbonded and bonded CFRP strip have almost an identical effect on the stiffness improvement of steel beams. Prestressed unbonded CFRP strips could, however, prevent fatigue crack initiation (Ghafoori et al. 2015c) and propagation (Aljabar et al. 2016, Ghafoori et al. 2012a, Ghafoori and Motavalli 2016b, Hosseini et al. 2017a) in steel plates and beams. In summary, the results of the extensive tests have shown that the static and fatigue behavior of steel beams are strongly governed by the prestress level in the CFRP strip, rather than the effect of the adhesive bonding. Bonded and unbonded systems have shown relatively similar results, particularly in the linear-elastic domain (Ghafoori 2015).

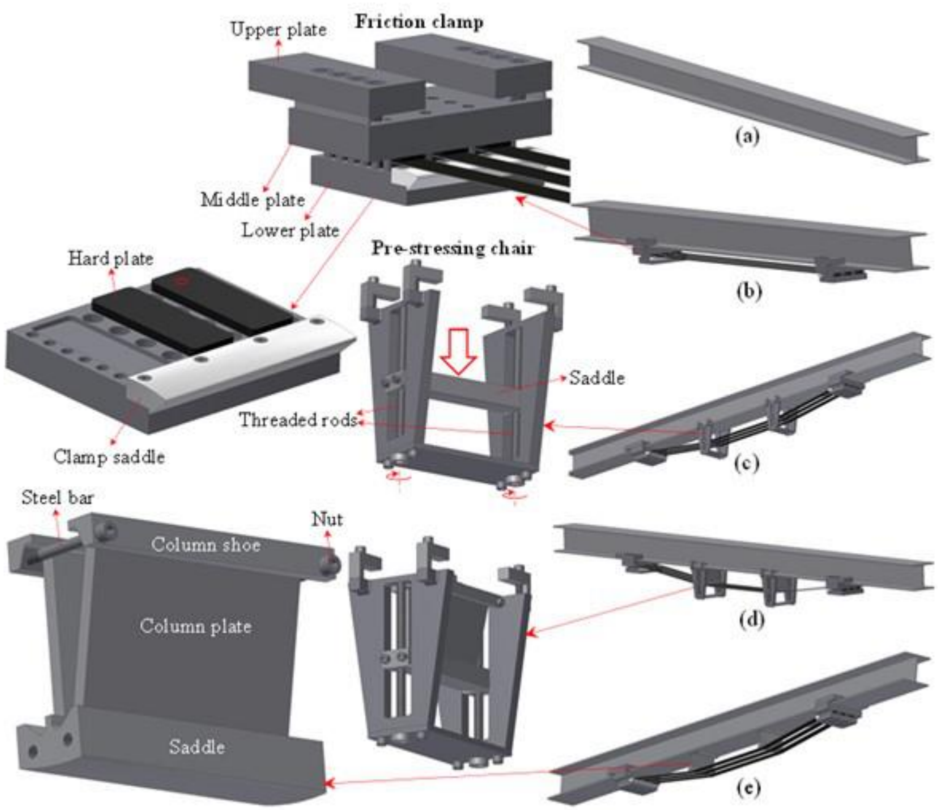


Figure 4. Different elements of the trapezoidal retrofit system: a) initial state of the beam, b) clamps are fixed, and the CFRP plates are placed between the two clamps, c) using pre-stressing chair, the saddle pushes the CFRP plates away from the beam that induces pre-stress in the CFRP plates, d) two plates are positioned between the beam and the saddle, and e) the pre-stress chair is removed (Ghafoori and Motavalli 2015a).

Figure 3a shows a PUR system with straight CFRP strips. Ghafoori and Motavalli 2015a have recently developed and patented a trapezoidal PUR system for strengthening of a historical metallic railway bridge in Switzerland. A summary of the prestressing procedure is explained as follows. Assume an I-beam as shown in Figure 4a. First, the mechanical clamps are placed near two ends of the beam, and three parallel CFRP plates are placed and tightened inside the clamps, as shown in Figure 4b.

Each CFRP plate has dimensions of 50 mm width and 1.2 mm thickness. Each friction clamp is consisted of a lower plate, a middle plate and two upper plates. The middle and the lower plates consist of three hard plates, which provide a uniform stress distribution along the CFRP anchorage length. Each CFRP plate is anchored between the lower plate and the middle plate and is subjected to compressive force, which is applied by pre-tensioned bolts. The beam flange is also gripped between the middle plate and the upper plates and subjected to the compressive force of pre-tensioned bolts. A pre-stressing chair is used to increase the eccentricity between CFRP plates and steel beam, as shown in Figure 4c.

The pre-stressing chair consists of a saddle that can move along two vertical threaded bars. The distance between the saddle and the beam can be manually changed by turning the threaded rods using a wrench. Thus, by turning the threaded rods, the saddle pushes the CFRP plates away from the beam, and the CFRP pre-stress is increased. A larger eccentricity between the CFRP plates and the beam corresponds to a larger CFRP pre-stress level. After the desired pre-stress level is achieved, two plates are placed between the CFRP plates and the beam (see Figure 4d). Each plate is positioned between the saddle and a shoe. The two shoes are connected by two steel bars and four nuts, as shown in Figure 4e, and then the pre-stressing chair is removed. Figure 4e shows the final configuration of the strengthened beam. More details can be found incan be found in Ghafoori and Motavalli 2015a, Ghafoori et al. 2015a. More recently, Kianmofrad et al. 2017) have suggested four different variants of the prestressed PUR systems: trapezoidal PUR (TPUR), triangular PUR (TriPUR), flat PUR (FPUR), and contact PUR (CPUR) systems for steel I-beams, while another PUR system for fatigue strengthening of tensile steel members has been introduced at Empa by Hosseini et al. 2017a. The behavior of each system has been examined using numerical, analytical and experimental investigations and, certain advantages and drawbacks of each system have been discussed.

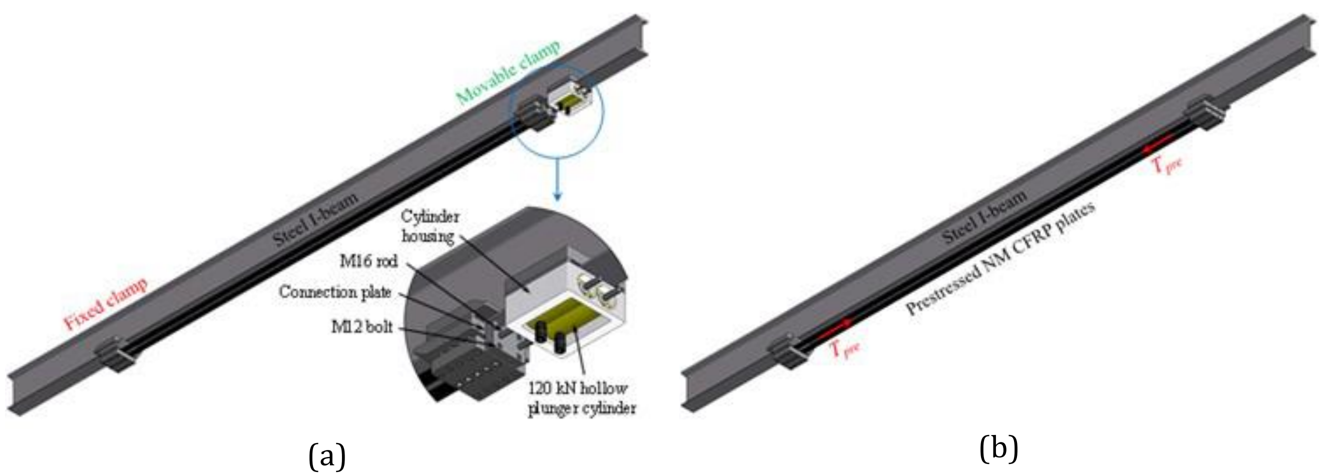


Figure 5. The FPUR system: (a) installation of the prestressing system and applying the required prestressing level; (b) fastening the movable clamp and removing the prestressing system ([Hosseini et al. 2018](#)).

Furthermore, Hosseini et al. 2018 have developed and tested a FPUR system. The FPUR system relies on two sets of mechanical clamps i.e. the so called fixed clamp on one side, and the movable clamp on the other side of the beam (Figure 5). The two sets of the mechanical clamps are capable of transferring the prestressing force of the CFRP plates to the lower flange of a metallic I-shaped girder via friction. Each set of the mechanical clamps holds two prestressed normal modulus (NM) CFRP plates with cross-sectional dimensions of 50 × 1.4 mm (width × thickness). The strengthening procedure using the proposed FPUR system consists of the following three steps:

1) Installation of the mechanical clamps and the non-prestressed CFRP plates (see Figure 5): on both sides of the beam, the unstressed CFRP plates are sandwiched between 16-mm thick toothed plates installed inside the lower plate and upper plate with five prestressed bolts. The bolts generate a total gripping force. On one side of the beam (left side in Figure 5) the beam bottom flange is sandwiched between the upper plate and the over-flange plate by fastening eight bolts. This results in a full gripping force between the fixed clamp set and the beam bottom flange. On the other side of the beam, the unstressed CFRP plates are sandwiched in the movable clamp, while this clamp set is free to move horizontally along the beam axis for prestressing.
2) Installation of the prestressing system, applying the required prestressing force, and fastening the movable clamp (see Figure 5a): two hollow plunger cylinders are installed adjacent to the movable clamp using especial cylinder housing. The cylinder housing is anchored to the beam bottom flange in a similar way as the fixed clamp set. With the help of two threaded rods, the movable clamp can be pulled using the hollow plunger cylinders connected to a manual hydraulic pump, and subsequently, the CFRP plates can be prestressed. Upon reaching the desired prestressing level in the CFRP plates all the eight bolts of the movable clamp will be tightened, which leads to the design gripping force between the mechanical clamping system and the beam flange.
3) Removing the prestressing system to realize the final configuration as depicted in Figure 5b: after reaching the desired prestressing force in the CFRP plates, the hydraulic pressure can be released and the entire prestressing system consisting of the two hollow plunger cylinders and the cylinder housing can be removed.

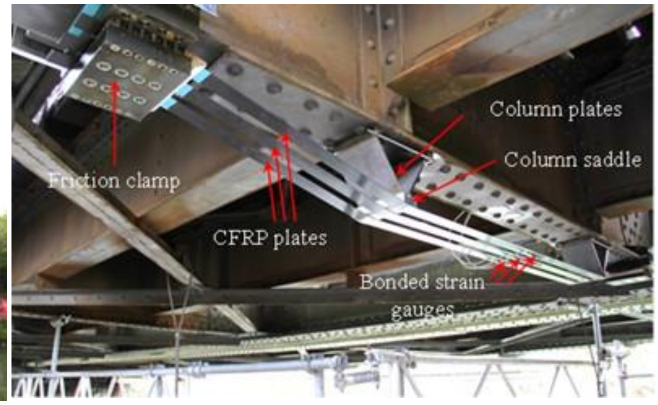
STRENGTHENING OF METALLIC BRIDGES

Strengthening of a railway riveted bridge in Switzerland

The Münchenstein Bridge was constructed in 1875 by G. Eiffel. The bridge is located near Basel City over the river Birs in Switzerland. In 1891, after 15 years of service, the bridge suddenly collapsed when a passenger train was passing across it. The disaster took the lives of 73 passengers and is historically the worst railway accident ever in Switzerland. A single-span riveted bridge was then constructed in 1892, as a replacement for the collapsed one. The bridge, as shown in Figure 6a, consists of 10 frames and was constructed approximately 5 m above the water level. The total length of the bridge is approximately 45.2 m. The bridge is subjected daily to both passenger and freight trains. After successful laboratory tests of the TPUR system (see Figure 4), several cross-girders of the bridge were strengthened with the system. Figure 6b shows a riveted cross-girder of the bridge after strengthening. Furthermore, to ensure no slip occurs between the CFRP plates and the clamps and also between the friction clamps and the metallic beams, one strain gauge was glued on each CFRP plate and the prestrain level was monitored using a wireless sensor network (WSN) system.

Because strain gauges do not automatically compensate for temperature, for each active strain gauge, a dummy strain gauge was used to compensate for the effects of temperature variations. The dummy strain gauges, which are identical to the active strain gauges, were mounted to unstrained CFRP plates and placed near the active gauges. To account for the temperature effects, the dummy strain gauges were wired into a Wheatstone bridge on an arm adjacent to the active strain gauge.

(a)



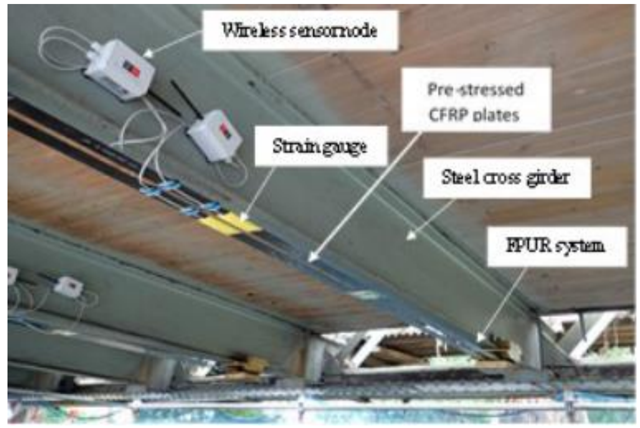
(b)

Figure 6. (a) Münchenstein railway metallic Bridge (120-year-old) subjected to a passenger train. The bridge consists of 10 panels with the total length of 45.2 m, width of 5 m and height of 6.15 m and built on a 45-deg skew. (b) The cross-girders were retrofitted with pre-stressed un-bonded CFRP strips (Ghafoori et al. 2015b).

Strengthening of a roadway metallic bridge in Australia

After successful laboratory tests on the FPUR system (see Figure 5), the system was applied on two cross girders of a roadway metallic bridge called SN6091 Bridge over Diamond-Creek along Heidelberg-Kinglake Road in Victoria, Australia (see Figure 7a). The steel I-shaped cross girders were strengthened with the proposed FPUR system having a prestressing level of about 38%. A WSN system was installed on the bridge for long-term monitoring of the strain levels in prestressed CFRP plates. Figure 7b shows the applied FPUR and the WSN systems on the cross girders of the so called Diamond-Creek Bridge. Sets of truck loading (e.g., see Figure 7a) were performed before and after strengthening of the bridge, which showed the effectiveness of the FPUR system to reduce the bending stresses in the bottom flange of the girders (Ghafoori et al. 2018). The long-term performance of the system will be monitored at least for one year using the installed WSN system.

(a)



(b)

Figure 7. (a) Diamond-Creek Bridge, Melbourne, Australia, (b) application of the FPUR system for CFRP strengthening of the bridge cross-girders (Ghafoori et al. 2018).

CONCLUSIONS

The two main differences between the behaviour of CFRP–concrete and CFRP–metal bonded members are concerned with the failure mode and the stiffness of the retrofitted members. These differences resulted in the development of different CFRP prestressing concepts for strengthening of concrete and metallic members, which were briefly explained in this paper. For strengthening of metallic members, laboratory test results showed that adhesive bond does not significantly improve the static and fatigue behaviour of retrofitted steel beams; however, CFRP prestressing plays an important role. Therefore, in order to minimize the concerns related to effects of high ambient temperatures, moisture, freeze/thaw cycles or fatigue loading on the performance of the CFRP-to-metal bonded joints, a PUR system has been recently developed. The PUR system includes a novel friction-based mechanical clamping system for strengthening of metallic I-beams. Furthermore, some details about strengthening of a 120-year-old railway metallic bridge in Switzerland as well as an old roadway bridge in Australia using prestressed unbonded CFRP strips were given.

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I-75 BRIDGE OVER SEXTON/KILFOIL DRAIN, THE LONGEST HIGHWAY BRIDGE SPAN PRESTRESSED WITH CFRP STRANDS

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ABSTRACT

Extensive experimental, analytical, and numerical research efforts resulted in the design and construction of the world longest highway bridge span prestressed with carbon fiber reinforced polymer (CFRP) strands. This 137-ft (41.8-m) long simply-supported bulb-T beam bridge carries I-75 highway over Sexton/Kilfoil Drain in Allen Park, Michigan, U.S.A. The bridge superstructure is composed of ten 72-in. (1.83-m) deep precast prestressed bulb T beams supporting a 9-in. (230 mm) thick cast-in-place reinforced concrete deck slab. One exterior beam is prestressed with a total of 69 CFRP strands due to the weight of an additional sound barrier wall, while the rest of the beams are prestressed with a total of 63 strands each. Each strand is tensioned with an initial prestressing force of 35 kip (156 kN), which represents approximately 65 % of the strand guaranteed strength after it is reduced with the appropriate environmental reduction factor. To ensure the safety and adequacy of the bridge to carry the assigned traffic loads and withstand the severe weather in Michigan, the design of the bridge underwent multiple revisions and test results from a parallel experimental investigation were utilized to make key design decisions. In addition, a finite element study was executed to evaluate the response of the bridge under different loads and environmental conditions. Furthermore, after bridge construction and before it was opened for traffic, a field load test using two standard trucks positioned at strategic locations on the bridge was executed. The strain and deflection values of three beams due to the truck loads were captured using onboard sensors. Field

data were analysed and compared with finite element results and theoretical models to ensure adequate bridge performance.

KEYWORDS

Highway bridge, Prestressing CFRP, Field test, Bridge Design.

INTRODUCTION

Michigan Department of Transportation (MDOT) pioneers in the deployment of innovative materials such as non-corrosive CFRP to enhance the design, construction, and durability of highway bridge beams. This is partly motivated by the harsh Michigan weather and the overwhelming corrosion and durability issues associated with steel prestressed beam bridges. The use of CFRP as prestressing and reinforcement material started in Michigan in 2001 with the construction of Bridge Street bridge in Southfield, MI. Since then, several bridges have been successfully designed and constructed with CFRP components. For instance, in 2011, a two-span side-by-side precast prestressed box-beam bridge was constructed to carry Pembroke Rd over M-39 in Detroit, MI. The bridge is transversely post-tensioned with twelve 1.57-in. (40-mm) diameter un-bonded carbon fiber composite cable (CFCC) strands. In 2012, a three-span side-by-side box beam bridge carrying M-50 over NSRR railroad in Jackson, MI was also constructed and transversely post-tensioned using twenty un-bonded CFCC strands. In 2013 and 2014, two simply-supported 45°-skewed precast prestressed spread box-beam bridges were constructed to carry the east and west bounds of M-102 over Plum Creek in Southfield, MI. The box-beams are prestressed with 0.6-in. (15.2-mm) diameter CFCC strands and are provided with CFCC stirrups in the transverse direction. The cast-in-place deck slabs for both bridges are also reinforced with CFCC strands. In 2016, a 102.5-ft (31.2-m) long simply-supported bulb T-beam bridge was constructed to carry M-86 over Prairie River in Centreville, MI. Each of its seven bridge beams is prestressed with 59 CFCC strands with a diameter of 0.6 in. (15.2 mm). The latest and longest completed bridge project (Oct 2017) with CFRP reinforcement is carrying I-75 highway over Sexton and Kilfoil Drain in Allen Park, MI. This single span simply-supported bridge has an effective span of 137 ft (41.8 m) and a deck width of 63.3 ft (19.3 m) with a clear roadway of 60 ft (18.3 m). The bridge is composed of ten bulb T beams supporting a 9.0 in. (230-mm) thick cast-in-place reinforced deck slab. Before the bridge was opened for traffic, a field load test was executed by placing two 55-kip (245-kN) trucks at key locations near the mid-span and recording the response of the bridge using onboard sensors. The response of the bridge was compared with that expected theoretically and with the results from a finite element model. This manuscript documents some of I-75 bridge design and construction issues and provides the results of field load test.

I-75 BRIDGE OVER SEXTON/KILFOIL DRAIN

Design

Mechanical and physical properties of CFRP affect some design aspects of CFRP prestressed beams. For instance, jacking and prestress level is limited by the one-million-hour creep rupture strength of CFRP. Currently ACI 440.4R-04 limits the jacking stress to 65 % of the guaranteed strength although recent studies suggest much higher creep rupture strength. In addition, the coefficient of thermal expansion of CFRP is nearly negligible compared to that of concrete. Therefore, CFRP prestressed beams experience increase or decrease in the effective prestressing force with the increase or decrease in temperature, respectively. This kind of thermal gain or loss in prestressing force shall be considered when establishing the initial prestressing force. Other types of prestress loss such as elastic prestress loss and long-term loss due to concrete creep and shrinkage do not seem to be affected by the properties of the reinforcement and can be calculated using conventional equations and approximate methods developed for steel prestressed beams.

Once the prestressing force level is established, the analysis of a CFRP prestressed section becomes a straightforward process with few exceptions. For instance, steel reinforced/prestressed sections are classified as tension-controlled or compression-controlled according to the net tensile steel strain at the time the concrete in compression reaches its assumed crushing strain limit of 0.003. However, CFRP reinforced/prestressed sections are classified as tension or compression-controlled based on the actual failure mode whether it is crushing of the concrete or rupture of the CFRP reinforcement. If the concrete reaches a crushing strain of 0.003 while the net strain in the extreme CFRP remains less than net guaranteed tensile strain, the section is regarded as compression-controlled section. If the net extreme CFRP strain reaches the net guaranteed tensile strain, while the concrete compression strain remains less than 0.003, the section is regarded as tension-controlled. The net guaranteed tensile strain is the net tensile strain in the reinforcement at balanced strain conditions. For all prestressed CFRP reinforcement, the net guaranteed strain limit may be taken as the specified guaranteed ultimate strain exclusive of the strain due to prestress, creep, shrinkage, and temperature.

Whether the section is compression-controlled or tension-controlled, the nominal moment capacity can be calculated using the principles of strain compatibility and force equilibrium in the section. ACI 440.4R-04 provides equations to calculate the depth of the neutral axis and nominal moment capacity of the section when the reinforcement or prestressing CFRP are provided in a single layer. Nevertheless, due to the elastic nature of CFRP material, when the tension CFRP reinforcement is distributed over multiple layers, the failure of tension-controlled sections is usually governed by the failure of CFRP reinforcement at the extreme layer, which is the layer farthest from the compression fiber. CFRP reinforcements at layers closer to the compression fiber are likely to fail progressively once CFRP reinforcement at the extreme layer fails. It is therefore not recommended to sum the layers of CFRP reinforcements through their center of gravity. ACI 440.4R-04 Section 3.4.2 provides a set of equations to address this problem. Nevertheless, the equations in ACI 440 are based on the assumption that the stress distribution in concrete is linear and the section is tension-controlled and therefore, those equations are not applicable for compression-controlled sections or tension-controlled section with non-linear stress distribution on the concrete. That leaves the designer with the option of using basic strain compatibility and force equilibrium. However, strain compatibility and force equilibrium in their raw format tend to be a lengthy iterative process, especially when the mode of failure is not known.

To facilitate the flexural design and reduce the potential for error, a unified design approach is developed by converting the areas of CFRP reinforcement at different layers to equivalent areas at the level of the extreme CFRP layer using appropriate area reduction factors. The sum of equivalent reinforcement areas at the extreme layer is regarded as "The equivalent area of reinforcement, A_{fe}" and is used to calculate the depth of the neutral axis and the nominal moment capacity of the section. In other words, the equivalent area of CFRP reinforcement is a discrete area of CFRP reinforcement positioned at the extreme CFRP layer that results in the same flexural capacity of n layers of reinforcement.

The area reduction factors needed to calculate the equivalent areas of reinforcement are obtained by assuming linear strain distribution through the depth of the section. Thereby, the area of CFRP reinforcement at the ith layer is reduced with a factor depending on the distance from the ith layer to the extreme layer. The area reduction factor can be calculated by evaluating the strain distribution through the section as follows:

The net tensile strain at any layer (i) is related to the net tensile strain at the extreme CFRP layer by:

$$\varepsilon_i = \varepsilon_1 \left(\frac{d_i - c}{d_1 - c}\right) \tag{1}$$

where:

ε_i = net tensile strain at the ith CFRP reinforcement layer

ε_1 = net tensile strain at the extreme CFRP layer

d_i = depth of the ith CFRP layer from the extreme compression fiber (in. or mm)

d_1 = depth of the extreme CFRP layer from the extreme compression fiber (in. or mm)

c = depth of neutral axis from the extreme compression fiber (in. or mm)

The tensile force, T_i, in any CFRP layer (i) may be calculated as:

$$T_i = \varepsilon_i N_i a_f E_f = \varepsilon_1 \left(\frac{d_i - c}{d_1 - c}\right) N_i a_f E_f = \varepsilon_1 \left(\frac{d_i - c}{d_1 - c} N_i a_f\right) E_f = \varepsilon_1 A_{fe(i)} E_f \tag{2}$$

where:

ε_i = net tensile strain at the ith CFRP reinforcement layer

N_i = number of CFRP strands in the ith layer

a_f = area of single CFRP strand in the ith layer (in.^{2} or mm^2)

E_f = elastic modulus of CFRP (ksi or MPa)

d_i = depth of the ith CFRP layer from the extreme compression fiber (in. or mm)

d_1 = depth of the extreme CFRP layer from the extreme compression fiber (in. or mm)

c = depth of neutral axis from extreme compression fiber (in. or mm)

where $A_{fe(i)}$ is the area equivalent to the area of CFRP reinforcement at layer i and is calculated as:

$$A_{fe(i)} = \frac{d_i - c}{d_1 - c}(N_i\, a_f) \tag{3}$$

The equivalent area of reinforcement for the total reinforcement provided in the section, A_{fe} is calculated as:

$$A_{fe} = \sum_{i=1}^{n} A_{fe(i)} \tag{4}$$

Where

n = number of layers (rows) of CFRP reinforcement

At this stage of analysis, the depth of the neutral axis from the extreme compression fiber, c, can be initially set equal to $0.1d_1$. The initial assumption of $c = 0.1d_1$ is based on observations from multiple experimental flexural tests of CFRP prestressed beams. This assumption usually yields accurate estimate for the depth of the neutral axis and the flexural capacity of the section. It needs not to be adjusted unless more refined calculations are required. With $c = 0.1d_1$, Eq. 3 becomes:

$$A_{fe(i)} = \left(1 - \frac{s_i}{0.9d_1}\right)(N_i\, a_f) \tag{5}$$

where:

s_i = Distance between ith CFRP layer and extreme CFRP layer (in.) = $d_1 - d_i$

After establishing the equivalent area of reinforcement for the section, the exact depth of neutral axis shall be calculated from Eqs. 6 through 9, whichever is applicable:

For tension-controlled flanged sections:

$$c = \frac{E_f\, A_{fe}\left(\varepsilon_{gu} - \varepsilon_{pe}\right) + P_e - 0.85\, f'_c\, h_f\,(b - b_w)}{0.85\, f'_c\, \beta_1\, b_w} \tag{6}$$

For tension-controlled rectangular sections:

$$c = \frac{E_f\, A_{fe}\left(\varepsilon_{gu} - \varepsilon_{pe}\right) + P_e}{0.85\, f'_c\, \beta_1\, b} \tag{7}$$

For compression controlled flanged sections:

$$0.85\ f_c^{'}\,\beta_1\,b_w\,c + 0.85\ f_c^{'}\,h_f\,(b - b_w) = E_f\,A_{fe}\,\varepsilon_{cu}\left(\frac{d_1}{c} - 1\right) + P_e \tag{8}$$

For compression-controlled rectangular sections:

$$0.85\ f_c^{'}\,\beta_1\,b\,c = E_f\,A_{fe}\,\varepsilon_{cu}\left(\frac{d_1}{c} - 1\right) + P_e \tag{9}$$

where:

b = width of compression face of the member; for a flanged section in compression, the effective width of the flange (in. or mm)

P_e = effective prestressing force in the section (kip or N)

E_f = elastic modulus of CFRP (ksi or MPa)

ε_{cu} = average concrete crushing strain, 0.003

ε_{gu} = design guaranteed strain of CFRP including environmental and durability effects

ε_{pe} = effective prestressing strain in CFRP after subtracting applicable prestress losses

h_f = depth of compression flange (in. or mm)

b_w = width of web (in. or mm)

Equation 6 through 9 are developed by representing the natural relationship between concrete stress and strain by an equivalent rectangular concrete compressive stress block of $0.85 f_c^{'}$ over a zone bounded by the edges of the cross-section and a straight line located parallel to the neutral axis at the distance $a = \beta_1 c$ from the extreme compression fiber. The distance c is measured perpendicular to the neutral axis. The factor β_1 is taken as 0.85 for concrete strengths not exceeding 4.0 ksi (28 MPa). For concrete strengths exceeding 4.0 ksi (28 MPa), β_1 is reduced at a rate of 0.05 for each 1.0 ksi (6.89 MPa) of strength in excess of 4.0 ksi (28 MPa), except that β_1 shall not be taken to be less than 0.65.

After calculating the depth of the neutral axis, the nominal moment capacity of the section can be calculated for flanged sections subjected to flexure about one axis and where the compression flange depth is less than $a = \beta_1 c$ as follows:

$$M_n = \sum_{i=1}^{n}\left[a_f\,N_i\,\varepsilon_i\,E_f\,\left(d_i - \frac{a}{2}\right)\right] + P_e\left(d_p - \frac{a}{2}\right) + 0.85\ f_c^{'}\,h_f\,(b - b_w)\left(\frac{a}{2} - \frac{h_f}{2}\right) \tag{10}$$

where:

a_f = area of single CFRP strand in the ith layer (in.2 or mm2)

N_i = number of CFRP strands in the ith layer

ε_i = net tensile strain at the ith layer of CFRP reinforcement determined from strain compatibility, taken equal to $\varepsilon_1\left(\frac{d_i-c}{d_1-c}\right)$

ε_1 = net tensile strain at the extreme CFRP layer

d_i = depth of the ith CFRP layer from the extreme compression fiber (in. or mm)

d_1 = depth of the extreme CFRP layer from the extreme compression fiber (in. or mm)

$f_c^{'}$ = specified compressive strength of concrete at 28 days, unless another age is specified (ksi or MPa)

P_e = effective prestressing force in the section (kip or N)

d_p = distance from the extreme compression fiber to the centroid of prestressing strands (in. or mm)

E_f = elastic modulus of CFRP (ksi or MPa)

h_f = depth of compression flange (in. or mm)

b = width of compression face of the member (in. or mm)

b_w = width of web (in. or mm)

a = $\beta_1 c$; depth of the equivalent stress block (in. or mm)

β_1 = stress block factor

c = depth of neutral axis from extreme compression fiber as determined from Eqs. 6 through 9, whichever is applicable (in. or mm)

n = number of layers (rows) of CFRP reinforcement

For rectangular sections subjected to flexure about one axis, where the approximate stress distribution is used and where the compression flange depth is not less than $a = \beta_1 c$ as determined in accordance with Eqs. 6 through 9, whichever is applicable, the nominal flexural resistance M_n may be determined by using Eq. 10, in which case b_w shall be taken as b.

For I-75 bridge, all beams except one exterior beams were prestressed with a total of 63 CFCC strands with a diameter of 0.6 in. (15.2 mm), cross sectional area of 0.179 in.^{2} (115.4 mm^2), guaranteed tensile strength of 339 ksi (2.34 GPa), and elastic modulus of 21,000 ksi (147 GPa). Due to a significant dead load on the exterior beam, the number of CFCC strands increased to 69 strands for this beam only. All strands are prestressed with an initial prestressing force of 35 kip (156 kN) per strand. Figure 1 shows the cross section and prestressing layout in the beams. The transverse reinforcement, top flange reinforcement and deck reinforcement were made of epoxy coated steel reinforcing bars. During design, the Service Limit State was the governing state in establishing the number of strands based on the required level of prestressing force. The beams were designed to have no tension in the bottom flange under Service Limit State. Nominal moment capacity was calculated according to the equivalent area method and the results were verified by force equilibrium and strain compatibility of the section. Loads and distribution factors of bridge beams conformed to AASTHO LRFD (2014) design specifications. In addition, the bridge is provided with a single steel diaphragm at the mid-span as shown in Figure 1 and cast-in-place concrete diaphragms at the ends that were poured with the deck slab.

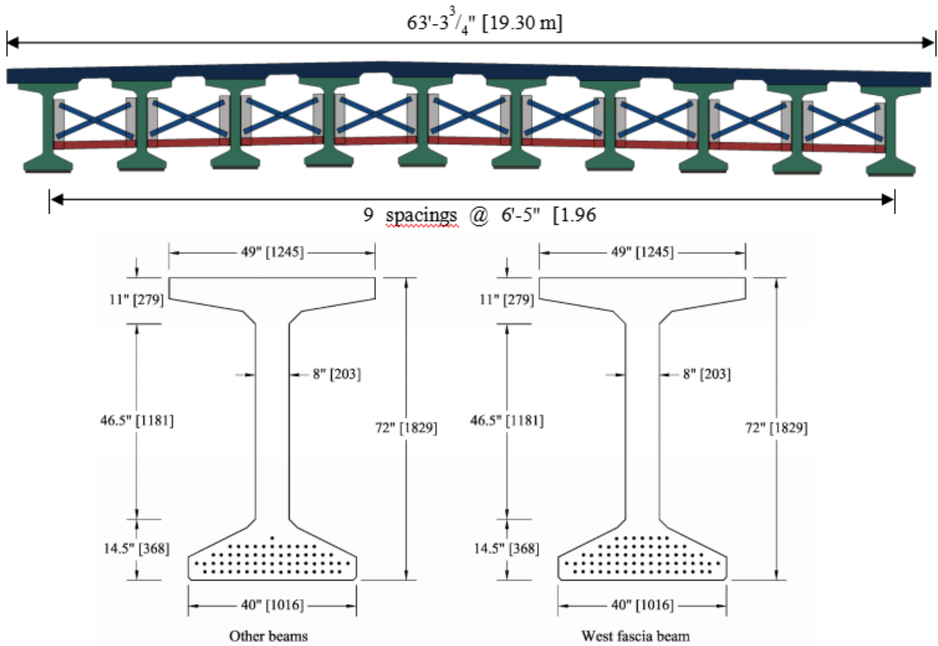


Figure 1: Cross section and distribution of prestressing CFCC strands in bridge beams

Finite Element Analysis (FEA) and Bridge Construction

Prior to beam construction, three finite element models were generated to simulate different stages of bridge construction and loading. The first model represented a single beam without a deck slab at the precaster plant. The beam model was analysed under initial prestressing force and the self-weight to evaluate the stresses and the camber in the beam at the time prestress release and during shipping and handling. The second finite element model represented a single beam with a deck slab. The model was analysed under construction and dead loads and an incremental live load represented by a two-point-load at the mid-span (four-point-loading setup). The live load was increased gradually until the failure of the beam model and consequently the numerical nominal moment capacity of the beam was determined. The third model simulated the full bridge and was analysed under effective prestressing force, dead loads, superimposed dead loads, wind loads, and traffic loads represented by a vehicular loading HL-93 according to AASHTO LRFD (2014) accompanied by extreme environmental conditions such as hot and cold weathers.

After verifying all design criteria using the FEA, construction of the beams was approved. The beams had a length of 138.33 ft (42.16 m) and were constructed in an abutment-type prestressing bed. To facilitate beam construction, CFCC strands were coupled with low-relaxation steel strands at both ends using a special coupler system. This enabled construction crew to execute the prestressing using conventional hardware that is used for steel. Prestress loss due to change in temperature from the time of prestressing to the time of pouring the concrete was estimated and considered in the jacking force. Due to concerns with high tensile stresses at beam ends during shipping and handling, the beams were constructed using a concrete mix with a design 28-day compressive strength of 10 ksi (69 MPa) and strength at release of 8 ksi (55 MPa). Figure 2 document different stages of beam and bridge construction.

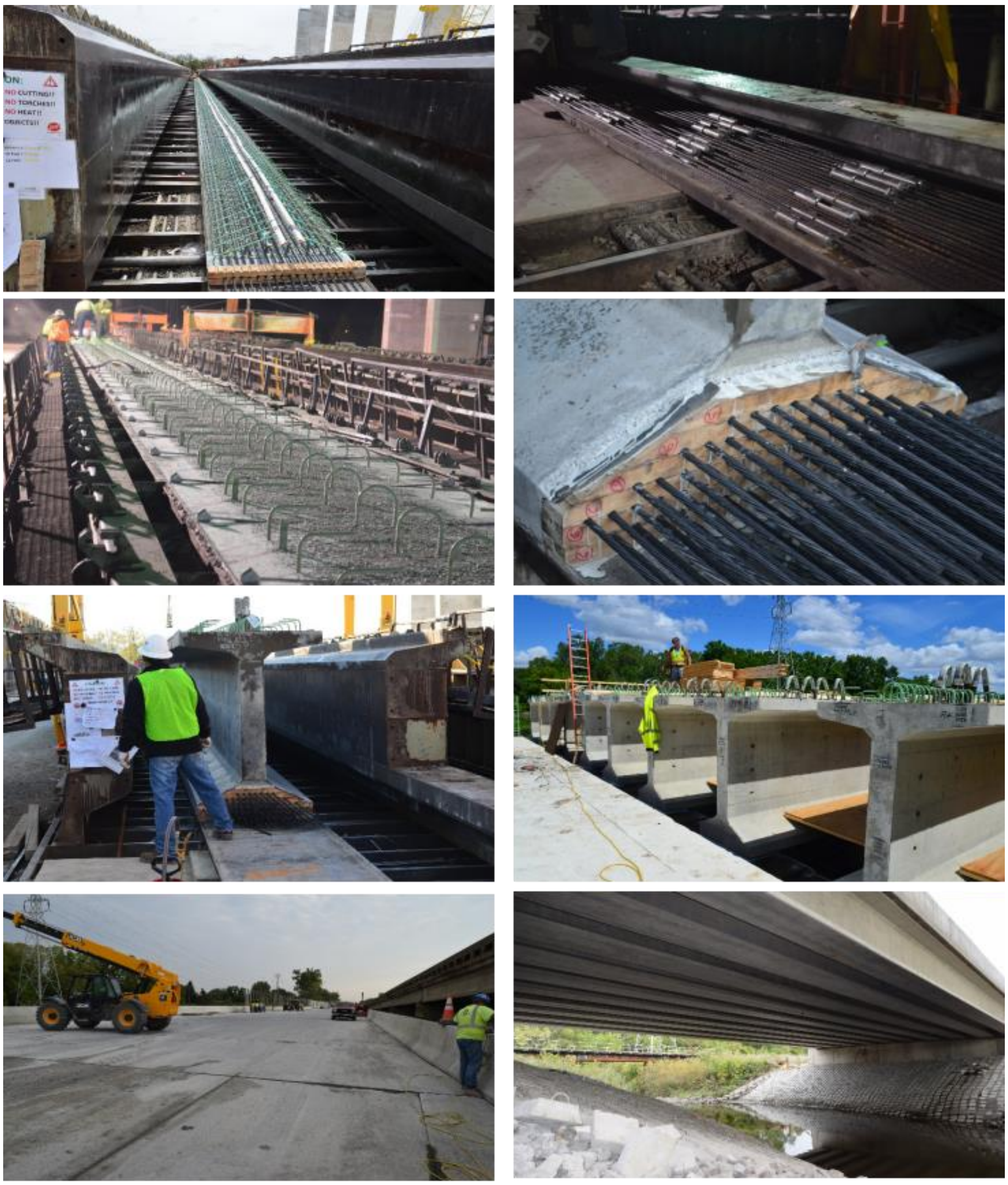
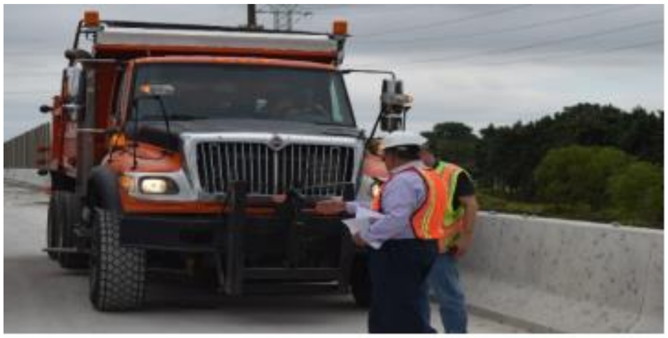


Figure 2: Construction of I-75 bridge over Sexton/Kilfoil Drain

Field Load Test



I: One truck on Lane 1

II: Two trucks on Lanes 1 & 2

III: Two trucks on Lanes 2 & 3

IV: Two trucks on Lanes 3 & 4

V: Two trucks on Lanes 4 & 5

VI: One truck on Lane 5

VII: Two back-to-back trucks on Lane 1

Figure 3: Seven truck locations during field load test using two 7600 international trucks

After completing the bridge construction and before it was opened for traffic, a field load test was executed to evaluate the bridge response and verify the design parameters. Two loaded 7600 international trucks, weighing approximately 55 kip (245 kN) each, were used to execute the load test. The clear bridge width of 60 ft (18.3 m) was divided into five 12-ft (3.7-m) wide lanes and the two trucked were positioned at seven locations as shown in Figure 3 near the bridge mid-span. The last location included placing the two trucks back-to-back (BTB) at the first lane near the exterior beam. Readings from strain gages attached to three beams were collected. In addition, the deflection of the beams was captured using a total station. Furthermore, the finite element model was analysed under the weight of the field trucks at the seven different locations. The stress, strain, and deflection due to truck loads at each location were estimated from the FEA and plotted against the anticipated theoretical values and the measured values from the field.

RESULTS AND DISCUSSIONS

As shown in the figures 4 and 5, there is a good agreement between the field strain readings and the finite element model. In addition, the deflection readings agreed well with those from the FEA. Furthermore, the reserve capacity of the bridge was determined by estimating the strain due to the design HL-93 vehicular loading and comparing the values with those obtained from the field test.

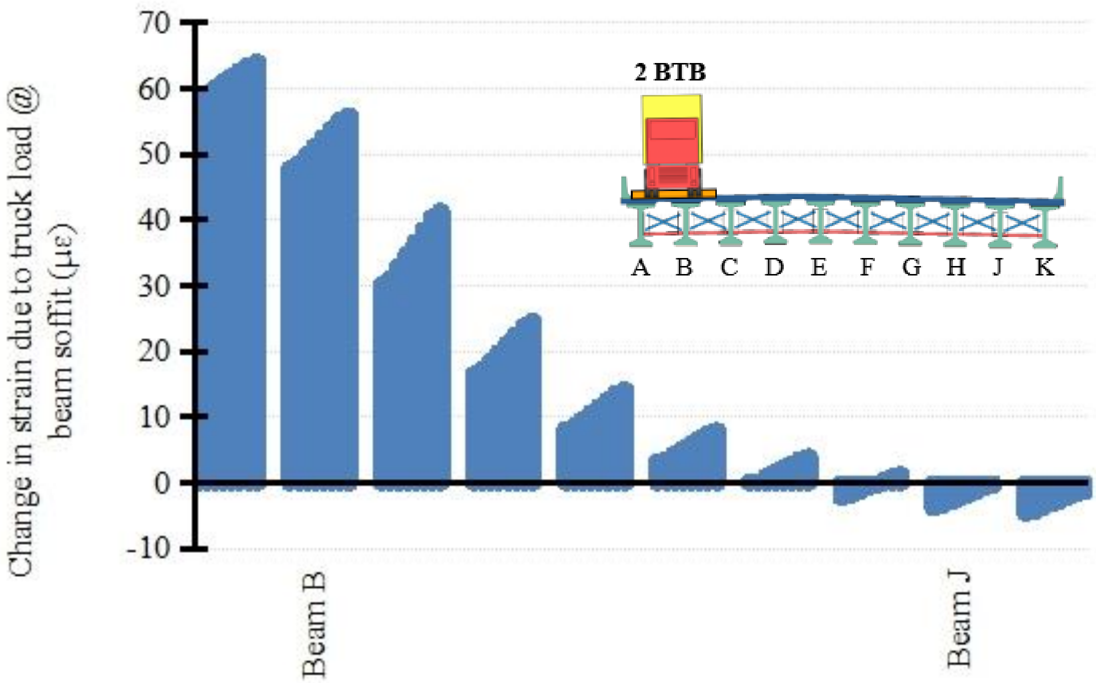


Figure 4: Change in strain in bridge beams due to two back-to-back field trucks (FEA)

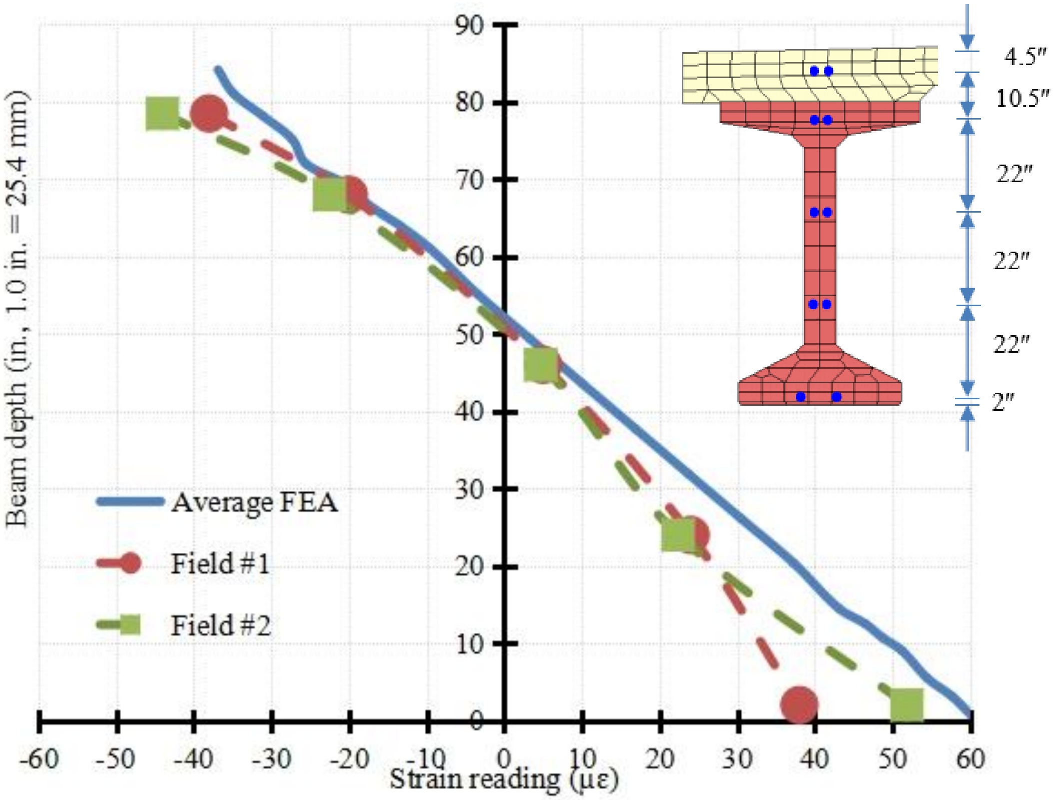


Figure 5: FEA and measured strain readings in Beam A due to two back-to-back field trucks @ lane 1

CONCLUSIONS

Results from the field load test verified the adequacy of the design procedure and the results of the finite element study. They also provided confidence in the CFRP material and the full bridge to support traffic loads. Therefore, it can be concluded that design and construction of highway bridges with CFRP reinforcement is a promising technique to mitigate the corrosion problem. With the appropriate design philosophy and the proper handling for the CFRP material, the design and construction can be a straightforward process.

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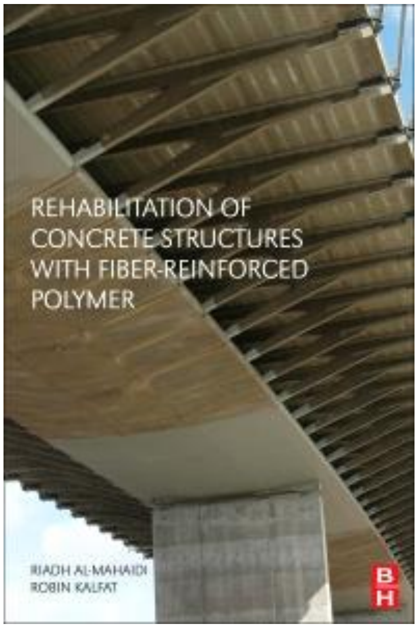
A New Book - Rehabilitation of Concrete Structures with Fiber-Reinforced Polymer



Rehabilitation of Concrete Structures with Fiber Reinforced Polymer is a complete guide to the use of FRP in flexural, shear and axial strengthening of concrete structures. Through worked design examples, the authors guide readers through the details of usage, including anchorage systems, different materials and methods of repairing concrete structures using these techniques. Topics include the usage of FRP in concrete structure repair, concrete structural deterioration and rehabilitation, methods of structural rehabilitation and strengthening, a review of the design basis for FRP systems, including strengthening limits, fire endurance, and environmental considerations.

In addition, readers will find sections on the strengthening of members under flexural stress, including failure modes, design procedures, examples and anchorage detailing, and sections on shear and torsion stress, axial strengthening, the installation of FRP systems, and strengthening against extreme loads, such as earthquakes and fire, amongst other important topics.

Key Features

- Presents worked design examples covering flexural, shear and axial strengthening
- Includes complete coverage of FRP in concrete repair
- Updated with the most recent guidelines (ACI40, TR55 and fib task group 9.3)

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Corrosion-Damaged RC Beams Repaired with Fabric-Reinforced Cementitious Matrix

Volume 22, Issue 6. December 2018

A PolyU-leading project was awarded the largest grant in the latest round of Theme-based Research Scheme

A project led by Prof. Jin-Guang Teng of the Department of Civil and Environmental Engineering (CEE), The Hong Kong Polytechnic University, has been awarded a grant of more than HK$47.2 million to develop a new type of concrete structures for marine infrastructure. The amount of funding is the largest among the five projects selected in the eighth round of Research Grants Council (RGC) Theme-based Research Scheme 2018/19.

In addition to the funding from the RGC, the local participating universities in the project will provide over HK$5.2 million as matching funding, bringing the total budget of the project to more than HK$52.4 million.

Entitled "Sustainable Marine Infrastructure Enabled by the Innovative Use of Seawater Sea-Sand Concrete and Fibre-Reinforced Polymer Composites," the project targets to address the severe deterioration problem of marine infrastructure caused by steel corrosion by replacing steel with fibre-reinforced polymer (FRP) as the reinforcing material. This replacement then will allow the direct use of seawater and sea-sand in making the concrete (i.e., seawater-sea-sand concrete or SSC in short). Eventually marine infrastructure will enjoy a longer life span, while energy consumption and environmental pollution will be less in the construction process.

Prof. Jin-Guang Teng, Chair Professor of CEE, PolyU, said, "PolyU is very pleased to learn the funding results and is very happy to be able to lead such a significant and impactful research project. With the use of the new type of structures (FRP-SSC structures) in marine infrastructure, great environmental and economic benefits can be derived not only for Hong Kong but also for the nation and the whole world. "

Typically, steel corrosion costs an economy around 3% of its gross domestic product (GDP). In the case of Hong Kong, 3% of the GDP in 2017 amounts to over HK$79.8 billion. The American

Society of Civil Engineers (ASCE) estimated in 2013 that US$3.6 trillion (equivalent to over HK$28.2 trillion) would be needed in the following eight years to maintain a state of good repair for the US infrastructure.

The research project will include the development of innovative steel-free structural forms as well as new methods for the design, construction and performance monitoring of FRP-SSC structures. A key scientific challenge for the team is the establishment of a multi-scale, multi-physics approach for predicting the long-term performance of FRP-SSC structures in a marine environment over a service life of more than 50 or even 100 years. Results obtained with this method will assist greatly in the formulation of safe and economical design methods for FRP/SSC structures.

Co-principal investigators include: Prof. Christopher K.Y. Leung from the Hong Kong University of Science and Technology; Prof. Zong-Jin Li from the University of Macau; Prof. Yi-Qing Ni and Prof. Chi-sun Poon from PolyU CEE; Dr Florence Sanchez from Vanderbilt University in the US; Prof. Tong Sun from City, University of London; Mr Sheng-Nian Wang from the CCCC Fourth Harbour Engineering Institute Co. Ltd. in the mainland China; and Prof. Li-Min Zhou from PolyU's Department of Mechanical Engineering.

The project will take five years to complete (i.e. by December 2023), with partial results becoming available at various stages of the project.

\- *END* -

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