FRP INTERNATIONAL

the official newsletter of the International Institute for FRP in Construction

Vol. 10, No. 3, July 2013

CICE 2014
Vancouver, Canada
August 20-22, 2014

Invitation to CICE 2014

Dr. Raafat El-Hacha,
Chair of CICE 2014

On behalf of the International Institute for FRP in Construction (IIFC), it gives me great pleasure to invite all to the 7th International Conference on FRP Composites in Civil Engineering (CICE 2014), the official conference of the IIFC, to be held in Vancouver, British Columbia, Canada from August 20-22, 2014. The conference is co-hosted by the University of Calgary and the University of British Columbia.

CICE 2014 aims to provide an international forum where leaders, engineers, researchers, practitioners and industrial partners in the field of fibre reinforced polymer (FRP) composites in civil engineering can discuss, exchange, and share recent advances and developments and future perspectives of the use of FRP in bridges and other structures. The CICE 2014 conference will continue the success of CICE conferences held in Hong Kong 2001, Adelaide 2004, Miami 2006, Zurich 2008, Beijing 2010, and Rome 2012. The CICE 2014 conference is organized into several focus areas including: FRP for Sustainability, FRP Internal Reinforcement, FRP Strengthening, Hybrid FRP Structures, All-FRP and Smart FRP Structures, Durability and Long-Term Performance, Fire, Impact and Blast Loading, Inspection and Quality Assurance, Codes and Design Guidelines, Field Applications and Case Studies, FRP in 2020: Visions and Reality.

We also invite you to enjoy the spectacular beauty of Vancouver; voted one of the world's premier meeting and convention destinations and ranked #4 on the list of the world's 10 best places to live. Located halfway between Europe and the Asia Pacific region, Vancouver is located on Canada's spectacular West Coast, surrounded by mountains and ocean side beaches. The city of Vancouver is a cosmopolitan city with a vibrant and multicultural population of two million; it is safe, clean, and pedestrian friendly. Vancouver, the host city of the 2010 Winter Olympics and Paralympics Games, offers an unprecedented range of activities and experiences and unique attractions (Vancouver Aquarium, Capilano Suspension Bridge, Vancouver Art Gallery, Vancouver Maritime Museum, Museum Of Anthropology, Botanical Gardens…). The CICE conference will be held at The University of British Columbia (UBC), only 20 minutes to downtown or the Vancouver International Airport which offers direct flights to major cities around the world. The city centre is easily accessible by public transit, with many bus routes offering frequent service.

CICE 2014 promises to be an engaging and enjoyable meeting of International colleagues. There is a full companion program and plenty of activities for families. You may plan your pre- or post-conference vacations to Victoria and Vancouver Island, Whistler, Okanagan, the Canadian Rocky Mountains, or Alaskan cruises. We look forward to welcoming CICE 2014 delegates to Vancouver in August 2014!

More information is available online at www.cice2014.ca or by contacting cice2014@ucalgary.ca

ABSTRACTS ARE DUE 15 JULY 2013

FRP INTERNATIONAL
the official newsletter of the International Institute for FRP in Construction

20th Anniversary of *FRP International*
10th Anniversary of IIFC

2013 marks the 20th volume of *FRP International* and the 10th anniversary of the founding of IIFC (*FRP International* restarted with Vol. 1 when it became the official newsletter of IIFC). In its first 20 years, the 56 issues of *FRP International* have contained 194 research articles and 283 case studies or product reports. Articles have originated from 29 countries. Interestingly, articles focusing on external FRP reinforcement have outnumbered those addressing either internal FRP reinforcement or FRP structures and shapes by about 2 to 1. A complete index of all

FRP International articles is maintained on the IIFC website: www.iifc-hq.org.

Considering the milestone anniversaries of both *FRP International* and IIFC, over the course of this year we are featuring a few items from twenty and ten years ago... The use of FRP in construction has come a long way in a very short time. Why it only seems like yesterday...

Twenty Years Ago…

The Summer 1993 (Vol. 1 No. 3) *FRP International* was introduced by Mr. Peter Head, founding director of Maunsell Structural Plastics. By 1993, Mr. Head had already more than decade's experience integrating composite materials in the construction industry. This experience culminated in 1992 with the design and construction of then, the longest GFRP bridge in the world, the Aberfeldy Golf Club footbridge (also featured in Vol. 1, No.1).

Limited funds were available for construction and maintenance and a highly optimised design, using polyester GFRP decks and towers, was adopted allowing the bridge to be assembled on economical foundations using student labour from the University of Dundee. The bridge was designed using a limit-states design approach supported by static and dynamic finite element analyses. Extreme wind and flooding loads were both critical design conditions for the 63 m long cable-stayed span.

The structure was built of patented interlocking pultruded planks and connectors bonded together on site. The 113 m long deck is continuous over the main span and both back spans. The bridge was sufficiently light (the towers weight only 2.5 tonnes and the 2.1 m wide deck weighs 150 kg/m) that it was constructed and launched within eight weeks using a typical crew of six students and no crane.

Completed in October 1992 only a year after inception of the project, the bridge almost immediately experienced the worst flooding and winds ever experienced in the area. Twenty years on, The structure remains iconic to the FRP industry and is garnering renewed interest as the subject studies on FRP durability.

thehappypontist.blogspot.com

FRP International Vol. 1 No. 3 also features brief articles on a large variety of AFRP, GFRP and CFRP internal reinforcing products; although perhaps the highlight is an article by a young faculty member, Prof. Lawrence Bank (the accompanying photo of a twenty-year younger Prof. Bank is certainly worth logging into the IIFC website for). Prof. Bank notes that "glass and composite material technology could one day replace steel reinforcement in concrete bridges. … If the material proves successful, it could be an asset for the construction industry." It seems that Larry was on to something.

Ten Years Ago…

Ten years later, the Summer 2004 (Vol. 1 No. 2) *FRP International* featured reports of the application of FRP around the world. Considering Prof. Bank's prophetic comments a decade earlier, the progress was substantial. Articles in the summer of 2004 report on national standards and/or guidelines for FRP repair or FRP internal reinforcement issued in Canada, China, Europe, the UK and USA; all published in the years between 2000 and 2004. What a difference a decade makes.

This article describes recent research conducted at the University of Minho, the host institution of FRPRCS-11.

Flexural and Shear Strengthening of Reinforced Concrete Elements

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Prof. Joaquim Barros, ISISE, University of Minho, Portugal; barros@civil.uminho.pt

This work focuses on research carried out on the use of the near surface mounted (NSM) technique to increase the flexural capacity of statically indeterminate reinforced concrete (RC) slabs or shallow beams, and the use of embedded through-section (ETS) bars for shear strengthening of these structures.

NSM technique to increase the load carrying capacity of continuous RC slab strips

Experimental program

The potential of the NSM technique for increasing the load carrying capacity of two-span continuous RC slab strips was explored. Carbon fibre reinforced polymer (CFRP) laminates of rectangular cross section were used. The experimental program was composed of seventeen 5875 mm long RC slabs strips having section dimensions 375 x 120 mm strengthened with NSM-CFRP laminates, grouped in two series that were different in terms of their strengthening configuration: the ***H series***, were strengthened with NSM-CFRP applied in the hogging region only; and the ***HS series*** in which NSM CFRP is applied in both the hogging and sagging regions. Slab specimen configuration and identification is summarised in Table 1. Figure 1 shows the slab test configuration.

Table 1. Specimen identification.

Specimen	moment redistribution (η)	NSM-CFRP provided	target strength increase	strength increase observed
SL15	15%	none	-	-
SL30	30%	none	-	-
SL45-H & HS	45%	none	-	-
SL15s25-H	15%	H	25%	8.1%
SL15s25-HS	15%	H & S	25%	36.1%
SL15s50-H	15%	H	50%	19.8%
SL30s25-H	30%	H	25%	5.9%
SL30s25-HS	30%	H & S	25%	29.8%
SL30s50-H	30%	H	50%	9.2%
SL30s50-HS	30%	H & S	50%	49.4%
SL45s25-H	45%	H	25%	2.9%
SL45s25-HS	45%	H & S	25%	24.4%
SL45s50-H	45%	H	50%	8.5%
SL45s50-HS	45%	H & S	50%	37.2%

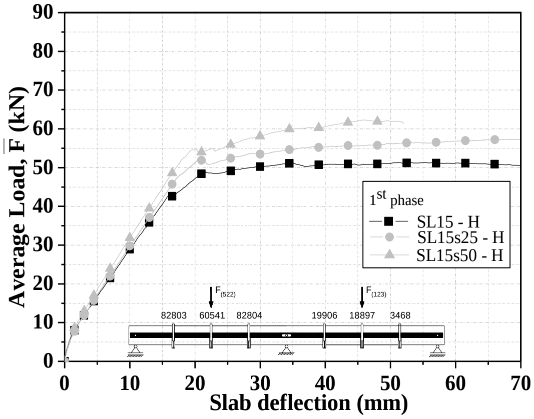
The amount and disposition of the steel bars were designed to assure moment redistribution percentages of 15%, 30% and 45%. The NSM-CFRP systems applied were designed for increases in load carrying capacity of 25% and 50% over the control slabs.

Figure 1. Test configuration.

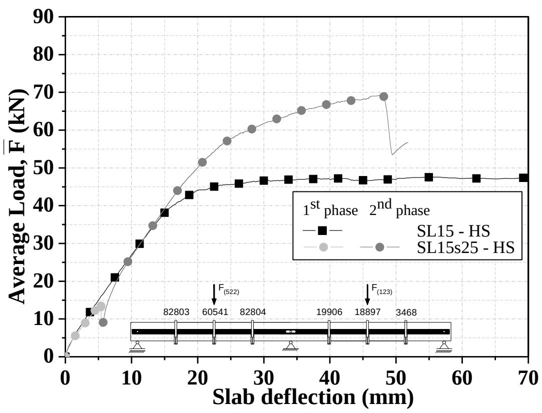
From the results obtained, shown in Table 1, it was verified that the strengthening configurations composed of NSM-CFRP applied only in the hogging region (H) did not attain the target increases of the load carrying capacity. In fact, when the CFRP laminates were applied in the hogging region, an increase of the load carrying capacity of between only 3 and 20% was achieved.

When NSM-CFRP was applied in both sagging and hogging regions (HS), an increase of the load carrying capacity was markedly greater and generally achieved the target capacity (Table 1). Therefore, to increase significantly the load carrying capacity of the RC slabs, the sagging zones need also to be strengthened. Figure 2 presents the load-midspan deflection of the slab strips SL15-H and SL15-HS. As seen in Figure 2, the NSM-CFRP strengthening configuration provided a significant increase of the load carrying during the second phase of the test loading process.

A lower-than-predicted moment redistribution (η) was observed in the slabs strengthened only in the hogging region. For this strengthening configuration, η decreases with an increase of the CFRP percentage. However, adopting a flexural strengthening strategy composed of NSM-CFRP applied in both hogging and sagging regions, resulted in the target values for η being attained; additionally, in this case, the influence of the percentage of CFRP was marginal on η. A detailed description of this experimental program is found in Dalfré (2013).



a) SL15-H



b) SL15-HS

Figure 2. Load-midspan deflection of the slab strips

Numerical simulations

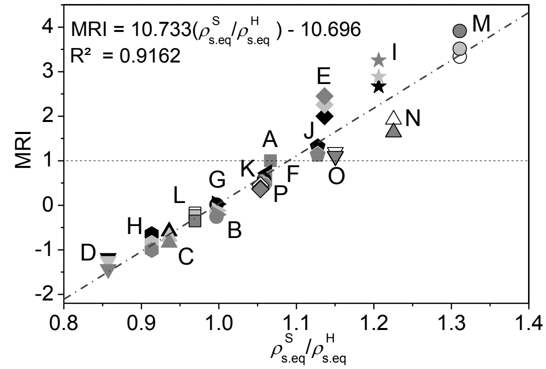
For assessing the predictive performance of a FEM-based computer program for the simulation of the behaviour of these types of structures, the experimental tests were simulated by considering the nonlinear behaviour of the constituent materials. The numerical simulations have reproduced with high accuracy the behaviour of the tests (Dalfré 2013).

A parametric study composed of 144 numerical simulations was carried out to investigate the influence of the strengthening arrangement and CFRP reinforcing ratio in terms of load carrying capacity and moment redistribution capacity of continuous RC slab strips flexurally strengthened by the NSM technique. According to the results, shown in Figure 3, the load carrying and the moment redistribution capacities strongly depend on the flexural strengthening arrangement described by the equivalent reinforcing ratio:

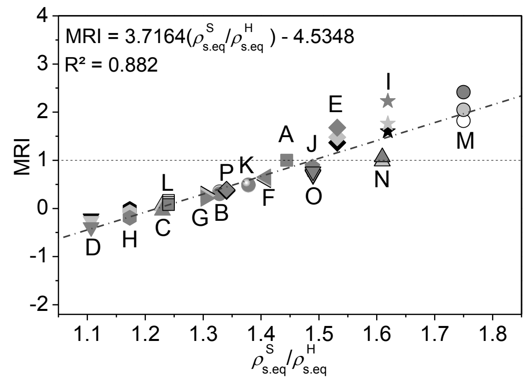
$$\rho_{S,eq} = A_s/bd_s + (A_f E_f/E_s)/bd_f$$

Where b is the width of the slab cross section; d_s and d_f are the effective depth of the longitudinal steel and NSM-CFRP, respectively; and E_s and E_f are the Young's Modulus of the longitudinal steel bars and NSM-CFRP, respectively.

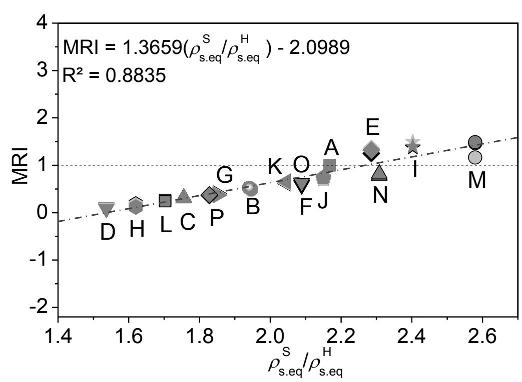
The load carrying capacity of the strengthened slabs increases with the equivalent reinforcement ratio applied in the sagging and hogging regions ($\rho^S_{s,eq}$ and $\rho^H_{s,eq}$, respectively), although the increase is more pronounced with $\rho^S_{s,eq}$, especially up to the formation of the plastic hinge in the hogging region.



a) SL15



b) SL30



c) SL45

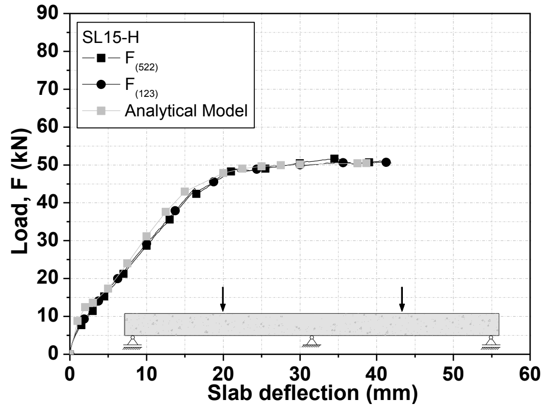
Figure 3. Relationship between the moment redistribution index and $\rho^S_{s,eq}/ \rho^H_{s,eq}$.

The moment redistribution index (*MRI)* is the ratio of moment redistribution factors of the strengthened and reference slabs: $MRI = \eta_{streng}/\eta_{ref}$; where η is the moment redistribution ratio at the formation of the second hinge (in the sagging region). According to the results, the *MRI* increases with $\rho^{S}_{s,eq}/\ \rho^{H}_{s,eq}$, and positive values (indicating that the moment redistribution of the strengthened slab is greater than its corresponding reference slab) are obtained when $\rho^{S}_{s,eq}/\ \rho^{H}_{s,eq} > 1.09$, $\rho^{S}_{s,eq}/\ \rho^{H}_{s,eq} > 1.49$, and $\rho^{S}_{s,eq}/\ \rho^{H}_{s,eq} > 2.27$ for η equal to 15%, 30% and 45%, respectively. Thus, the moment redistribution percentage can be estimated if $\rho^{S}_{s,eq}/\ \rho^{H}_{s,eq}$ is known. Figure 3 presents the relationship between *MRI* and $\rho^{S}_{s,eq}/\ \rho^{H}_{s,eq}$ for series SL15, SL30 and SL45. The results demonstrate that the use of efficient strengthening strategies can provide an adequate level of ductility and moment redistribution in statically indeterminate structures, with a considerable increase in the load carrying capacity. A flexural strengthening strategy composed of NSM-CFRP applied in both hogging and sagging regions has a deflection ductility performance similar to the corresponding RC slab. Finally, the rotational capacity of the strengthened slab strips decreases with the increase of $\rho^{H}_{s,eq}$, and increases with $\rho^{S}_{s,eq}$. In the slab strips strengthened in both hogging and sagging regions, a rotational capacity lower than the reference slabs was obtained.

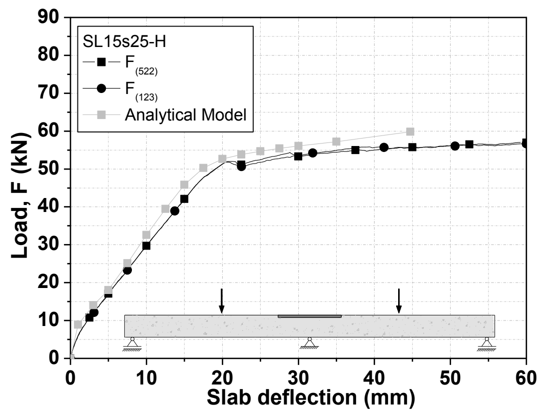
Analytical formulation

To predict the load-deflection response up to the collapse of statically indeterminate RC structures, an analytical model was developed and its predictive performance was appraised using the data obtained in experimental programs (Dalfré 2013).

The proposed approach is based on the force method of establishing a number of displacement compatibility equations that can provide the unknown variables. To determine the tangential flexural stiffness in these equations, moment-curvature relationships are determined for the cross sections representative of the structure. This model can be easily implemented in a design environment, and is applicable to statically determinate or indeterminate RC structures strengthened with the NSM or externally bonded (EB) reinforcement techniques. The predictive performance of the model was appraised by simulating the slab strips tested in the experimental program. The results, shown in Figure 4, showed that the developed numerical strategy is capable of capturing with enough accuracy the relevant features observed experimentally.



a) SL15-H



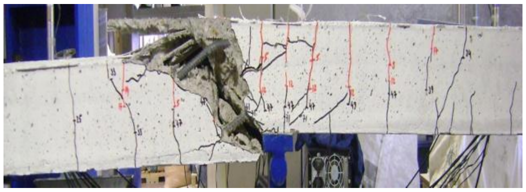
b) SL15s25-H

Figure 4. Relationship between applied load and deflections at spans of the slab strips.

ETS technique for shear strengthening RC elements

The effectiveness of the NSM technique can be compromised by the detachment of the concrete cover that includes the NSM-CFRP laminates and by formation of shear cracks in the hogging region of the flexurally strengthened elements (Figure 5). Moreover, in some cases, the failure mode shifts from ductile flexural failure to brittle shear failure following flexural strengthening. Shear failure of the retrofitted system must be avoided, since this failure is often brittle and occurs with little or no visible warnings. In this context the Embedded Through-Section (ETS) was applied for the shear strengthening of RC beams.

a) SL45s25-HS



b) SL45s50-HS

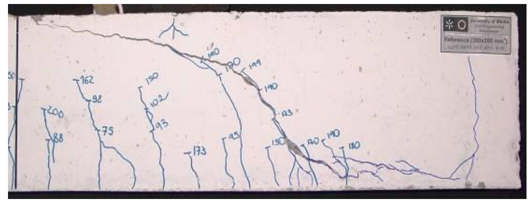
Figure 5. Failure mode of strengthened slab strips.

To assess the contribution of the bond mechanism of the ETS bars in the context of shear strengthening, and to better select the type of strengthening bars and adhesive materials, a comprehensive pull-out program was firstly executed (Dalfré 2013). Based on the results of this, steel bars and epoxy-based adhesive were selected for an ETS shear strengthening program with RC beams. The influence of the following parameters on the ETS shear strengthening effectiveness was investigated: spacing of the existing steel stirrups (225 and 300 mm), spacing (225 and 300 mm) and inclination (vertical and 45-degree) of the strengthening bars, and width of the cross section of the beam. The results obtained showed that, for the same shear strengthening ratio, the ETS technique provides increased levels of load carrying and deflection capacities, higher than those attained by FRP-based shear strengthening techniques (Dalfré 2013). An example of crack patterns and failure loads of ETS-strengthened slab strips is shown in Figure 6. According to the results, the ETS technique can be used to avoid the occurrence of shear failure in RC beams. Furthermore, the ETS technique uses low cost steel bars bonded to concrete with a cement based matrix that incorporates a small percentage of resin based-component. Since ETS steel bars have a relatively thick concrete cover, corrosion and injuries due to vandalism acts are not a concern.

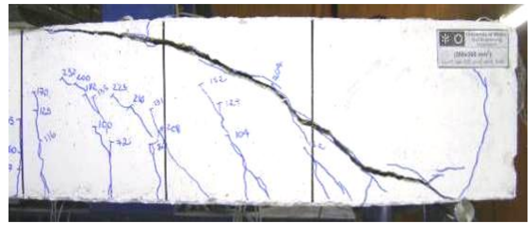
[copy edited by Kent A. Harries]

Reference

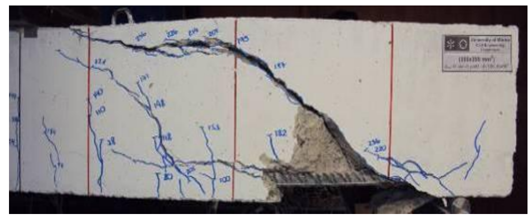
G. M. Dalfré, Flexural and shear strengthening of RC elements, PhD Thesis, University of Minho, Portugal (2013).



a) reference slab; F = 203.4 kN



b) steel stirrups at 90º and spacing of 300mm; F = 232.3 kN

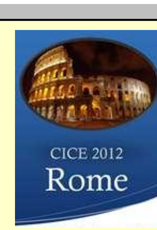


c) ETS bars at 90º and spacing of 300mm; F = 238.9 kN

d) ETS bars at 45º and spacing of 300mm; F = 336.2 kN

Figure 6. Crack pattern and failure load.

CICE 2012 Proceedings available on IIFC website



The complete Proceedings of CICE 2012 are now available on the IIFC website: www.iifc-hq.org.

All proceedings of official IIFC conferences presently archived on the IIFC website are:

CICE 2012, Rome, Italy, 13-15 June 2012

CICE 2010, Beijing, China, 27-29 September 2010

APFIS 2009, Seoul, Korea, 9-11 December 2009

CICE 2008, Zurich, Switzerland, 22-24 July 2008

APFIS 2007, Hong Kong, 12-14 December 2007

CICE 2006, Miami, USA, 13-15 December 2006

BBFS 2005, Hong Kong, 7-9 December 2005

This article was prepared based upon a keynote lecture delivered at CECOM 2012 in Krakow, Poland, 22-23 November 2012.

Structural Strengthening With CFRP Products – What We Know and What We Don't Know

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Prof. Wojciech Radomski, Lodz University of Technology and Warsaw University of Technology, Poland; w.radomski@il.pw.edu.pl

Structural strengthening using CFRP systems belongs to the most modern and advanced methods of structural strengthening. Beginning from 1991, when the method was first used to strengthen the Ibach Bridge in the canton of Lucerne, Switzerland, considerable development of structural FRP application has occurred all over the world.

CFRP products are used for structural strengthening of concrete, masonry, steel and timber structures. However, a great majority of their applications involve concrete structures. Therefore, this article focuses mainly on strengthening of concrete structures. The authors summarize the current Polish state-of-knowledge and identify several problems requiring further investigation.

There is a relatively great variety of CFRP products available for structural strengthening. The most popular examples applied for strengthening concrete structures are unidirectional laminates, bars, sheets, L-shaped elements and bidirectional fabrics and meshes. External CFRP tendons have been rarely used for structural strengthening in Poland so far. CFRP laminates and sheets are commonly used both for flexural and shear strengthening of reinforced concrete members such as beams and slabs; while in the case of columns, their strengthening for confinement is made by wrapping flexible CFRP fabrics, sheets or meshes. In general, CFRP structural strengthening systems can be classified into following groups:

Externally bonded (EB) reinforcement– the CFRP products are bonded with special adhesives to the external surface of RC members. The CFRP (mainly strips or sheets) can be bonded without or with prestressing (passive or active system, respectively) as well as without or with mechanical anchors;

Near surface mounted (NSM) reinforcement – the CFRP products, mainly strips or bars, are bonded into slots cut into the concrete cover of the element to be strengthened.

Strengthening with CFRP products requires special adhesives for bonding to the concrete substrate. In general, these are classified into two categories:

Epoxy-based resin adhesives - these may be bi-component viscous mixtures for adhering strips and L-shaped elements or saturants for impregnating for sheets and fabrics;

Mineral adhesive mortars or ***resin adhesives with inorganic binder*** – these are mainly used for sheets, fabrics and grids.

In order to reduce the stress concentration between the adhesive and the concrete substrate, typical for stiff epoxy adhesive layers, new research on CFRP-to-concrete bond behaviour using flexible polymer adhesives has been proposed. Such a stress reduction in the bond layer protects the concrete substrate from brittle local failure due to the presence of a shear stress singularity which may result in abrupt CFRP debonding in the concrete cover layer. Due to the stress reduction, a significant increase in the ultimate load of the strengthening system is observed, leading to an increase in effectiveness of the strengthening system.

Technological and material solutions versus economy

Technology and material solutions should be considered in their economic context. Therefore, it is justified to try to formulate criteria for the proper choice of the CFRP strengthening solutions. In the case of strengthening for flexure, the choice is rather limited: CFRP strips and sheets are commonly used for EB (in passive or active form) or NSM (passive) as described in Table 1. In the case of strengthening for shear, the choice is relatively wider: passive strips, sheets, fabrics and L-shaped elements can be used. Prestressed CFRP shear strengthening, according to the author's knowledge, has not been applied. Strengthening for confinement also has a limited choice of sheets and fabrics which may be wrapped around the columns in passive or slightly prestressed form. It is obvious that the strengthening costs are variable and highly dependent on the strengthening configuration.

The other parameter that should be considered in the strengthening decision is the substrate strength to which the FRP product is to be bonded. Above all, pull-off tests are necessary to determine the tensile strength of the substrate.

Economic analysis should be performed including not only the direct costs but also so-called the social costs. In other words, the time of strengthening operations should be considered as a very important parameter. It should be emphasized that the basic advantage of the use of passive CFRP strips for flexural strengthening is their very short installation time compared to other equivalent strengthening methods such as bonding thin steel plates.

It is worth recalling that when the Ibach Bridge was strengthened in 1991, the unit CFRP material cost was 40-50 times higher than the unit price of steel. However, instead of 175 kg of steel, 6.2 kg of CFRP strips were used, making the comparable material cost for CFRP only 160% greater. Taking into account the considerably shorter installation time, it can be concluded that this innovative method has been economically competitive from its very inception! Today, CFRP prices have fallen considerably in relation to steel.

It should be also pointed out that the use of passive CFRP strips for flexural strengthening does not permit their very high tensile strengths to be fully utilised. Strength utilisation is typically only 30-40%. Considering a high unit cost, this further affects the apparent economy of CFRP strengthening techniques. However, again considering savings in installation and deployment, this opinion also seems questionable.

On the other hand, taking advantage of the high tensile strength of CFRP is economically and technically justified. More recently, several practically useful methods of prestressing CFRP have been developed and implemented. Even though prestressing CFRP improves effectiveness of the material for flexural strengthening and enables higher CFRP strength utilisation, the prestressing technique is more time consuming and results in higher costs of installation and maintenance mainly due to the anchorage systems required. Therefore, the use of CFRP prestressing systems for flexural strengthening requires detailed

Table 1. Technical and economical factors for preliminary selection of CFRP strengthening methods for RC structures.

Required strengthening	Possible solution	Strengthening effectiveness	Relative cost with comments
A. Flexural strengthening of RC beams and slabs			
A.1 – Low (<15% strength increase)	EB - passive strips / sheets	High	Low –proper surface preparation of the RC member is required
	NSM - passive strips	Very high	Low – longitudinal grooves may be made without surface preparation
A.2 – Medium (15-30% strength increase)	EB - as in case A.1	Medium	Medium – more than one CFRP ply/ layer may be required
	NSM - as in case A.1	High	Low – as in case A.1
	Prestressed CFRP strips used to reduce passive strips used	Very high	High - strengthening operations are more complex compared to passive strengthening
A.3 – High (>30% strength increase	EB - as in case A.1	Low	Very high – more CFRP strips are needed
	NSM - as in case A.1	Medium	Medium – more CFRP strips are needed
	Prestressed CFRP strips	Very High	High – as in case A.2
B. Strengthening for shear			
B.1 – Low	EB – side bonding passive strips/sheets	Low	Low – some problems occur due to geometric limitation of effective bond lengths of CFRP strips
	EB –bonding passive L-shaped strips or U–shaped sheets	Medium	Medium – bonding of U and L-shaped elements requires preparation of corners
	EB - passive sheets/fabrics wrapping around the entire cross-section	High	Medium
B.2 – Medium	EB - strips, sheets, fabrics or U or L-shaped elements - as in case B.1	Medium	Medium
	NSM – passive strips placed into grooves on sides of the beam	High	Medium – vertical or inclined grooves are required
B.3 - High	EB – passive sheets/fabrics wrapping around the entire cross-section	High	High – more CFRP layers are needed; interference with slabs can increase complexity significantly
C. Strengthening for compression (axial/eccentric load)			
C.1 – Low	EB - wrapping of columns with passive sheets or fabrics	High	Low – if one CFRP layer is adequate
C.2 – Medium	EB - as in case C.1	High	Medium – more CFRP layers are needed
C.3 – High	EB - wrapping of columns with prestressed sheets or fabrics	Very high	High – strengthening operations are more complex compared to passive strengthening

Table 2. Future research issues in CFRP application.

Research issue	Comments
R.I. Materials issues	
R.I.1. Thermal properties of separate CFRP products and strengthening systems	The problem is understood in quantitative terms, particularly associated with the negative coefficient of thermal expansion of CFRP and AFRPs. There is very limited knowledge the qualitative aspect and the influence of thermal factors on the long-time durability of the strengthening system when a large temperature gradient occurs.
R.I.2. New generation of CFRP materials with properties more compatible with the those of the strengthened structures	CFRP products generally have higher characteristic strength and stiffness than the strengthened structural members. Therefore, strengthening with CFRP products, both in passive and active form, leads to a redistribution of internal forces in the structure. This can be a local or global effect. It is necessary to analyze the influence of the strengthening system used on this redistribution (e.g., too 'strong' local strengthening can lead to weakness of other parts of the structure compared to the original situation).
R.I. 3. Optimise properties of adhesives	There are a great variety of adhesives available to bond CFRP products to strengthened structures. Normally, the adhesives are provided as part of the CFRP strengthening system. However, the properties, particularly the stiffness, of the adhesives can vary significantly, resulting in different effectiveness of strengthening. Therefore, criteria for optimal selection of the adhesive is of prime interest for practitioners
R.II. Strengthening system issues	
R.II.1. Fatigue resistance	It is known that the CFRP products themselves show high fatigue resistance. However, *in situ*, fatigue behaviour has been shown to vary considerably, largely associated with the adhesive performance. Additionally, very little data is available for fatigue behaviour in low or high temperature environments; an issue critical for bridge structures.
R.II.2. Fire resistance	It known that the fire resistance of the CFRP systems is relatively low; again largely associated with the adhesive systems used. Protection of CFRP systems is an item of key importance for the broad acceptance of these systems.
R.III. Strengthening effectiveness and durability	
R.III.1. Active (prestressed) strengthening	In some strengthening solutions the prestressed CFRP strips are not bonded to the structural members (external 'tendons' analogous to post-tensioning). Such solutions reduce cost and complexity. However issues of long-term performance, especially creep and relaxation remain unaddressed.
R.III.2. Strengthening of plates and shells	A great majority of research and applications address the strengthening of beams. Limited information is available on the strengthening effectiveness of plate or shell elements. The required two-dimensional strengthening and the interaction of orthogonal 'layers' of CFRP must be addressed.

technical and economic analysis, with consideration of other general factors. These are described in Table 1 along with a commentary that may be useful for ***preliminary analysis and selection*** of strengthening methods. A few additional comments regarding Table 1 are appropriate:

i) The required level of structural strengthening should be determined based on the real condition of (e.g.: the loss of its original characteristics), and load demand (e.g.: strength and stiffness) on the structure. Moreover, it should be known whether the strengthening is required to restore the original structural characteristics or to upgrade these because of new service functions of the structure.

ii) Effectiveness of strengthening can be different depending on the application method. However, all methods have technical and economic limits. In some cases, regardless of approach, structural members may not be reasonably repaired and must be replaced.

iii) The costs presented in Table 1 are relative and concern strengthening with CFRP systems only.

Research problems

It is common that parallel to the development of practical applications of any engineering method, new issues appear requiring investigation and solution. This is no less true with CFRP strengthening techniques. The authors contend that the current state-of-art for CFRP strengthening is sufficient for the majority of practical applications. This is the baseline of "what we know". Nonetheless, research based on experimental and theoretical investigations and practical experience indicated many issues requiring further analysis and research. There are many important problems about which "we do not know". Similarly, we contend that there remain issues that "we do not know what we do not know". Some of the most important of these issues are presented in Table 2, presenting the authors' subjective opinion on these matters.

[copy edited by Kent A. Harries]

Innovative Research and Products

Behaviour of Pultruded GFRP Compression Members

Mr. Daniel C.T. Cardoso, University of Pittsburgh and Federal University of Rio de Janeiro

Dr. Kent A. Harries, University of Pittsburgh, USA kharries@pitt.edu

Dr. Eduardo de M. Batista, Federal University of Rio de Janeiro, Brazil

Although significant efforts are underway worldwide to develop reliable standards for the design of glass fibre reinforced polymer (GFRP) pultruded structural members, there remain a number of important gaps in the knowledge and understanding of the behaviour of these members. The majority of previous studies have addressed I-shaped sections comprised of slender flange plates, from which the following conclusions have been obtained: short column compressive strength is governed by local buckling; long columns fail by global buckling; and intermediate columns exhibit interaction between local and global buckling. A very limited number of works have investigated the behavior of square tube columns and none have established a relationship between wall slenderness and failure modes, an issue critical to the understanding of the overall column behavior.

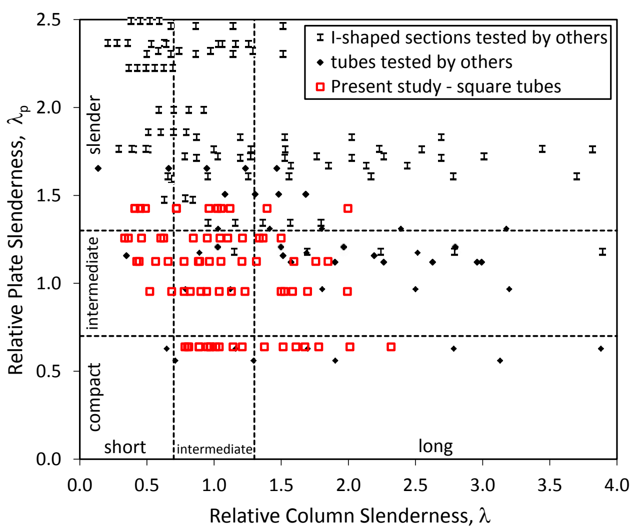


Figure 1. Summary of recent experimental works plotted according to wall and column slenderness.

Motivated by filling these gaps, an experimental program on the behavior of GFRP columns was undertaken at the Watkins-Haggart Structural Engineering Laboratory at the University of Pittsburgh. The study focused on square tube columns having different sections and lengths, resulting in combinations of column and wall slenderness, defined, respectively, as:

$$\lambda = \min\left[\sqrt{F_{cr\ell}/F_{cr}}, \sqrt{F_c/F_{cr}}\right]$$

$$\lambda_p = \sqrt{F_c/F_{cr\ell}}$$

Where F_{cr} is the critical global buckling stress, $F_{cr\ell}$ is the critical local buckling stress and F_c is the material strength. Figure 1 presents a summary of recent experimental works plotted according to λ and λ_p, from which it can be observed that the present study covers an important area with limited available data.

The experimental program was carried out in four stages: i) cataloguing cross-section geometry; ii) material characterization; iii) stub column tests; and iv) column concentric compression tests. From these stages, actual dimensions and properties to be used for accurate correlation between theory and experiments were obtained, critical loads and compressive strengths were captured, overall column behavior, including interactions between crushing, local and global buckling and post-buckling, were observed and column and wall imperfections were estimated. Figure 2 shows photographs from stub and column tests and failure patterns observed.

a) stub test showing local buckling

b) crushing at column end and midheight

c) column test showing global buckling

d) column test showing buckling interaction

Figure 2. Stub and column tests.

In the study, the critical loads were experimentally obtained using Southwell plots and a very good agreement between theory and experiments was obtained. The observed failure modes were 'mapped' according to wall and column slenderness (Figure 3). From this, the following conclusions were drawn: i) long columns exhibited large lateral deflection, regardless of wall slenderness; ii) short columns failed by either crushing or local buckling followed by crushing; iii) buckling interaction followed by crushing was observed for intermediate columns with $\lambda_p > 1$; and iv) crushing following global buckling was observed for intermediate columns with $\lambda_p < 1$. In the same Figure, colors indicate ranges of experimentally observed reduction factors ρ, defined as the ratio of observed ultimate strength to the predicted 'perfect' column capacity. It can be seen that the greatest strength reductions were observed for intermediate columns comprised of intermediate plates, a combination that has received little previous attention, despite being critical for pultruded tubular members.

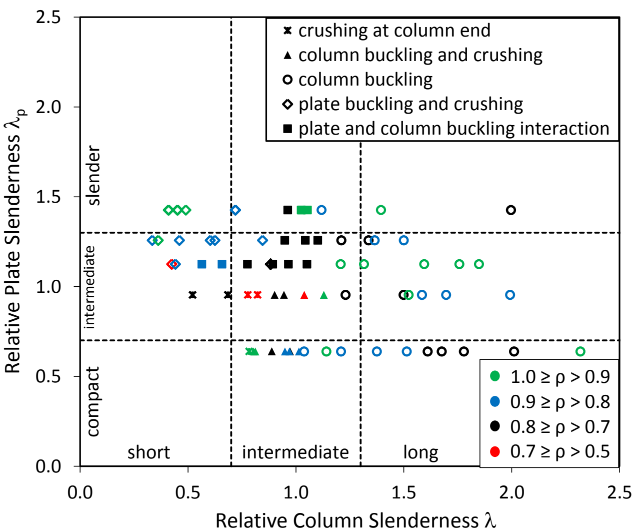


Figure 3. Column failure modes and capacity reduction factors based on column and plate slenderness.

Finally, it is remarked that the majority of previous studies have focused on I-shaped columns comprised of slender plates (see Fig. 1); these are not as critical and do not represent the greatest reductions in theoretical capacity. Thus, it is recommended that additional studies be carried out focusing on tubular column sections with both column and wall slenderness, λ and λ_p, classified as intermediate. Ongoing research is expanding this study and including other shapes in the intermediate slenderness category.

Innovative Research and Products

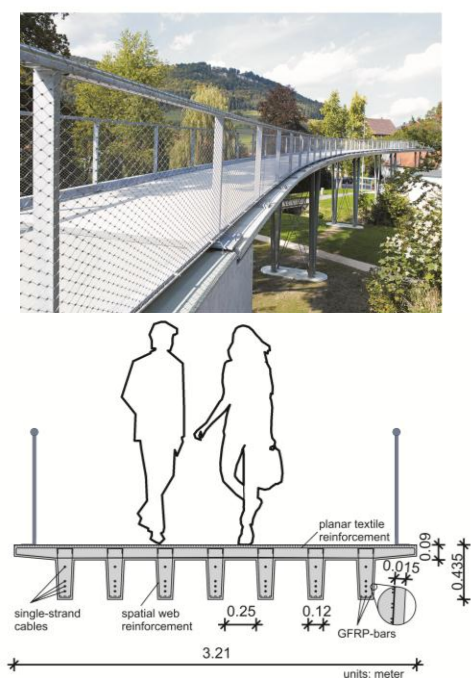
Innovative Pedestrian Bridge Made of Textile-Reinforced Concrete

Mr. Roland Karle, Groz-Beckert KG, Germany
roland.karle@groz-beckert.com

Prof. Dr.-Ing. Josef Hegger, RWTH Aachen University, Germany
imb@imb.rwth-aachen.de

Textile-reinforced concrete (TRC) uses mesh-like reinforcement structures, which are made of alkali-resistant glass or carbon filaments. Due to the non-corrodible properties of the textiles, the concrete cover can be reduced to some millimeters. In contrast to reinforced concrete structures, which need more than 40 mm for outdoor applications, slender and light-weight concrete constructions can be realized. One example is the pedestrian bridge in Albstadt, Germany, which has a TRC superstructure. The 97 m long bridge is subdivided in six precast elements each having a length of 17.2m. With a span of L = 15 m and a construction height of only H = 435 mm, an extremely slender construction was achieved (H:L = 1:34). Next to the textile reinforcements, single-strand cables and GFRP-bars were arranged in the webs of the T-beam.

Due to a concrete cover of only 15 mm, savings of 40% in weight and a reduction of 30% of carbon dioxide emissions allowing for a greener construction with economic advantages.



TRC pedestrian bridge in Albstadt, Germany.

ASCE *Journal of Composites for Construction*

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http://ascelibrary.org/cco/

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http://www.editorialmanager.com/jrncceng/

ASCE *Journal of Composites for Construction*, Volume 17, No. 2, pp 167-291. April 2013.

Flexural Behavior of Concrete Beams Internally Prestressed with Unbonded Carbon-Fiber-Reinforced Polymer Tendons

S. Heo, S. Shin, and C. Lee

Laboratory Characterization and Evaluation of Durability Performance of New Polyester and Vinylester E-glass GFRP Dowels for Jointed Concrete Pavement

Mathieu Montaigu, Mathieu Robert, Ehab A. Ahmed, and Brahim Benmokrane

Effect of Prestressing on the Performance of GFRP-Reinforced Concrete Slab Bridge Strips

Martin Noël and Khaled Soudki

Flexural Behavior of Unbonded Posttensioned Concrete Members Strengthened Using External FRP Composites

F. El Meski and M. Harajli

Experimental Study on the Flexural Behavior of RC Beams Strengthened with Steel-Wire Continuous Basalt Fiber Composite Plates

Gang Wu, Yi-Hua Zeng, Zhi-Shen Wu, and Wu-Qiang Feng

Bond-Slip Model for FRP Laminates Externally Bonded to Concrete at Elevated Temperature

Jian-Guo Dai, W. Y. Gao, and J. G. Teng

New Method of Strengthening Reinforced Concrete Square Columns by Circularizing and Wrapping with Fiber-Reinforced Polymer or Steel Straps

Muhammad N. S. Hadi, Thong M. Pham, and Xu Lei

Full-Scale Testing of CFRP-Strengthened Slender Reinforced Concrete Columns

Katarina Gajdosova and Juraj Bilcik

Structural Behavior of Arch Models Strengthened Using Fiber-Reinforced Polymer Strips of Different Lengths

Luisa Rovero, Francesco Focacci, and Gianfranco Stipo

Retrofitting Earthquake-Damaged RC Structural Walls with Openings by Externally Bonded FRP Strips and Sheets

Bing Li, Kai Qian, and Cao Thanh Ngoc Tran

Behavior of Hybrid FRP-Concrete-Steel Double-Skin Tubular Columns with a Square Outer Tube and a Circular Inner Tube Subjected to Axial Compression

T. Yu and J. G. Teng

Concrete-Filled FRP Tubes: Manufacture and Testing of New Forms Designed for Improved Performance

Togay Ozbakkaloglu

ASCE *Journal of Composites for Construction*, Volume 17, No. 3, pp 293-419. June 2013.

Design of RC Columns Using Glass FRP Reinforcement

Hany Jawaheri Zadeh and Antonio Nanni

Axial Load Behavior of Concrete Columns Confined with GFRP Spirals

Chris P. Pantelides, Michael E. Gibbons, and Lawrence D. Reaveley

Bond Strength of Lap-Spliced GFRP Bars in Concrete Beams

M. Reza Esfahani, Mehrollah Rakhshanimehr, and S. Roohollah Mousavi

Anchorage System to Prestress FRP Laminates for Flexural Strengthening of Steel-Concrete Composite Girders

Raafat El-Hacha and Mohamed Y. E. Aly

Mechanical Behavior of FRP-Strengthened Concrete Columns Subjected to Concentric and Eccentric Compression Loading

Xiaobin Song, Xianglin Gu, Yupeng Li, Tao Chen, and Weiping Zhang

Combination of Bamboo Filling and FRP Wrapping to Strengthen Steel Members in Compression

Peng Feng, Yanhua Zhang, Yu Bai, and Lieping Ye

Volume 17, No. 3, pp 293-419. June 2013, *continued*

Statistical Characterization of Reinforced Concrete Beams Strengthened with FRP Sheets

Yail J. Kim and Kent A. Harries

Numerical Investigation on the Hysteretic Behavior of RC Joints Retrofitted with Different CFRP Configurations

A. Dalalbashi, A. Eslami, and H. R. Ronagh

Functionality of Damaged Steel Truss Systems Strengthened with Posttensioned CFRP Tendon

Garrett Brunell and Yail J. Kim

Structural Optimization of FRP Web Core Decks

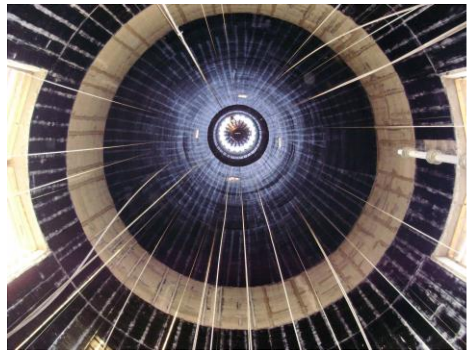
Ishan Srivastava, Tushar Kanti Dey, Anupam Chakrabarti, and Pradeep Bhargava

Progressive Failure and Ductility of FRP Composites for Construction: Review

Lawrence C. Bank

Congratulations to Structural Technologies, LLC.

Their 2012 IIFC Photo Competition winning entry will be featured on the cover the *ASCE Journal of Composites for Construction* throughout 2013.



Installation of 11,000 m^2 of CFRP sheets in a 140 m high chimney for seismic flexural strengthening.

IIFC members awarded ACI Chester Paul Siess Award for Excellence in Structural Research

Prof Luke Bisby and Dr Tim Stratford, along with Edinburgh University Master of Engineering students Jason Barrington and David Dickson, were recently awarded the American Concrete Institute's 2012 Chester Paul Siess Award for Excellence in Structural Research. This honor was bestowed by the ACI Board of Direction at its fall 2012 meeting for their coauthored paper that investigates the performance of FRP-wrapped square and rectangular columns. This paper is published in the Proceedings of the 10th International Research Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-10), which were also published as ACI Special Publication SP-275. Formal announcement of the award was made at the Opening Session and Awards Program of the ACI Spring 2013 Convention, Sunday, 14 April 2013 in Minneapolis, MN.

Luke Bisby and Jason Barrington (right) receiving Chester Seiss Award from ACI President President James K. Wight (left)
(photo courtesy of the American Concrete Institute)

The paper abstract is below:

Strain Development and Hoop Strain Efficiency in FRP Confined Square Columns

Abstract: The performance of FRP-wrapped square/rectangular columns depends on their corner radius, with larger corner radii resulting in superior confinement. However, the specific impacts of corner radius on the development of hoop strains in the FRP wraps are not well known. Most existing models for square FRP confined columns only indirectly consider the impacts of corner radius by inserting 'shape' factors into empirically calibrated models based on circular FRP confined columns. This approach cannot rationally account for the phenomena resulting from corner effects. This paper presents an investigation into the mechanics of square FRP confined concrete columns. It is shown that accounting for corner radius requires the inclusion of at least two modification factors: (1) a shape factor which accounts for the area of effectively confined concrete as well as the column's side aspect ratio, and (2) a variable strain efficiency factor which accounts for the adverse effects of decreasing corner radius.

For additional information please email Luke.Bisby@ed.ac.uk or Tim.Stratford@ed.ac.uk.

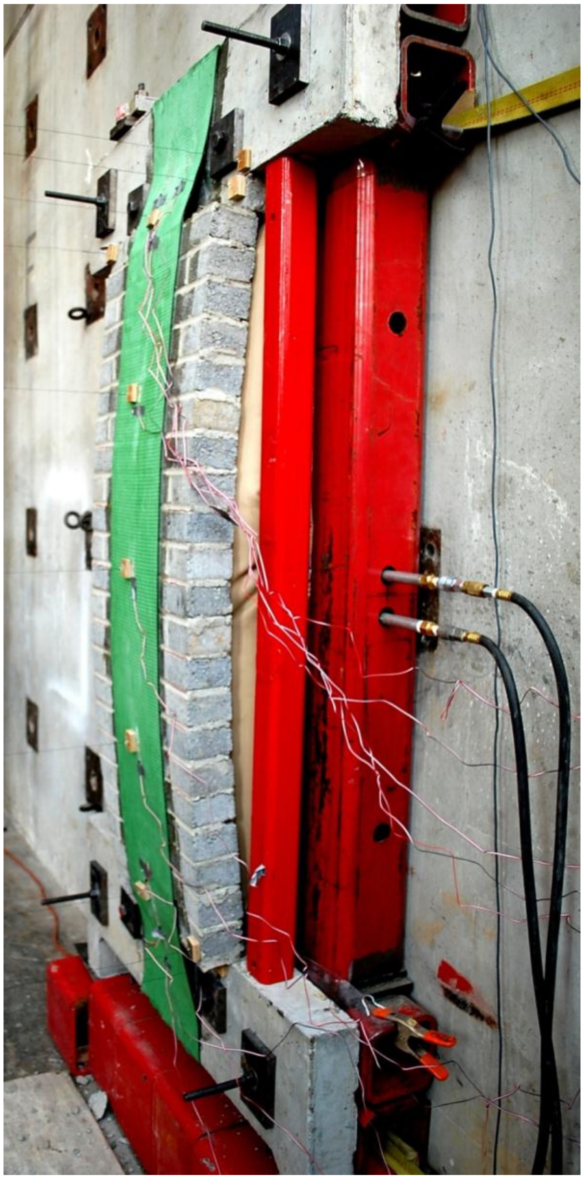
Recent Dissertations

Behavior and Modeling of Infill Masonry Walls Strengthened with FRP using Various End Anchorages

Dillon Lunn, PhD (2012)
North Carolina State University, Raleigh, NC, USA
Advisor: Prof. Sami Rizkalla

http://www.lib.ncsu.edu/resolver/1840.16/8270

Many existing unreinforced masonry infill walls are vulnerable to extreme out-of-plane loading such as the differential pressure caused by a tornado. Out-of-plane collapse of these structures is often catastrophic and could lead to severe property damage and loss of life. Retrofitting masonry infill walls with Fiber-reinforced Polymers (FRP) has recently been considered to increase strength and ductility and therefore reduce the risk of collapse under extreme loading conditions. Previous research has shown the potential for premature failure of the FRP strengthening system within the anchorage region where the FRP is connected to the supporting structure, which reduces the effectiveness of the strengthening system. The objective of this research program is to characterize the influence of end anchorage on the behavior of masonry infill walls strengthened with FRP materials subjected to out-of-plane loading through both experimental and analytical study and to provide a rational approach for the design of FRP-strengthening systems for masonry infill walls. The experimental program comprised twelve full-scale specimens consisting of two reinforced concrete (RC) caps (which simulate the supporting RC elements of a building superstructure) that were in-filled with solid concrete brick masonry and strengthened with FRP. The specimens were loaded by out-of-plane uniformly distributed pressure in cycles up to failure. The parameters investigated were the type of FRP material and the type of end anchorage. A finite element analysis (FEA) was conducted to predict the upper and lower bounds of the response, understand the effects of various design parameters, and characterize the failure mechanisms. A rational approach was developed based on four potential mechanisms: (1) arching, (2) shear sliding, (3) debonding of the FRP in the overlap region and (4) anchorage failure. Predictions based on the proposed rational approach agreed well with the measured values from this thesis as well as previous testing by the author of two-way infill walls and therefore it can be used effectively for the design of both the FRP-strengthening system and the end anchorage.



FRP-strengthened infill masonry wall using CFRP anchors, near failure.

IIFC encourages the announcement of recently completed theses and dissertations in FRP International*. Announcements should conform to the format shown and be sent directly to the editor at kharries@pitt.edu.*

Invitation to APFIS 2013

Profs Riadh Al-Mahaidi,
Xiao-Ling Zhao and
Scott Smith
Co-Chairs of APFIS 2013

On behalf of the Asia-Pacific Conference on FRP in Structures (APFIS2013) Committee, it gives us great pleasure to invite all to APFIS 2013 in Melbourne, Australia from 13 to 15 December 2013.

Melbourne is a vibrant community, typical of many cities in Australia. It has a well-developed infrastructure and a network of roads and bridges which serve a growing demand from users, particularly freight and road-users. Its bridge engineers, who are faced with many maintenance and rehabilitation challenges, will benefit greatly from exposure to the experience and knowledge of international FRP researchers and practitioners.

APFIS 2013 promises to be intellectually engaging and socially enjoyable. The following six keynote speakers will provide perspectives beyond those normally covered within the APFIS series. They come from varying backgrounds and therefore promise to be thought provoking.

Prof .Zdeněk Bažant, Northwestern University, USA
Dr. Geoff Taplin, AECOM, Australia
Prof. Hui LI, Harbin Institute of Technology, China
Prof. Yiu-Wing Mai, University of Sydney, Australia
Prof. Alper Ilki, Istanbul Technical University, Turkey
Dr. Jian-Guo Dai, The Hong Kong Polytechnic University, Hong Kong

The conference will be held prior to the end of year summer festive season. You may therefore use this opportunity to spend time in and around Melbourne and the state of Victoria in Australia. You may also use the opportunity to travel to other parts of Australia such as Sydney, Canberra and the Gold Coast.

We look forward to welcoming APFIS2013 delegates to Melbourne in December 2013.

Melbourne is home to the Westgate Bridge. The city's iconic structure is also of primary importance to the national transportation network. The 38 approach spans of the bridge were recently retrofitted with FRP, making it the world's largest FRP retrofitting project [see *FRP International*, Vol. 8, No. 3; available online at www.iifc-hq.org]. The bridge currently services approximately 160,000 vehicles per day compared with only 40,000 vehicles when it opened 30 years ago, with future predictions indicating escalating demands expected. The increased traffic volume is accommodated by the introduction of two additional lanes through the main carriageway to carry peak hour traffic. The retrofitting comprised of nearly 40 km of carbon fibre laminates along with 11,000 sq. m of carbon fibre fabric applied to the structure.

Upcoming Conferences and Meetings

2nd Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, September 9-11, 2013, Istanbul, Turkey. www.smar-2013.org

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ACIC 2013 *6th Advanced Composites in Construction,* September 10-13, 2013, Belfast, UK. www.acic-conference.com

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Innovative Composites Summit Americas 2013, October 2-4, 2013, Boston, USA. www.jeccomposites.com.

APFIS 2013 *4th Asia-Pacific Conference on FRP in Structures,* December 11-13, 2013, Melbourne Australia. www.apfis2013.org

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CICE 2014 *7th International Conference on FRP Composites in Civil Engineering*, August 19-22, 2014, Vancouver, Canada. www.cice2014.ca

Abstracts due: July 15, 2013

CICE 2016 *8th International Conference on FRP Composites in Civil Engineering*, June 2016, Hong Kong.

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the official newsletter of the International Institute for FRP in Construction

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As IIFC grows, we are also expanding the utility and reach of *FRP International*. The newsletter will continue to report the activities of IIFC and focus on IIFC-sponsored conferences and meetings. Nevertheless, we also solicit short articles of all kinds: research or research-in-progress reports and letters, case studies, field applications, or anything that might interest the IIFC membership. Articles will generally run about 1000 words and be well-illustrated. Submissions may be sent directly to the editor. Additionally, please utilize *FRP International* as a forum to announce items of interest to the membership. Announcements of ***upcoming conferences***, ***innovative research or products*** and ***abstracts from newly-published PhD dissertations*** are particularly encouraged. *FRP International* is yours, the IIFC membership's forum. The newsletter will only be as useful and interesting as you help to make it. So, again, please become an *FRP International* author.