FRP INTERNATIONAL

the official newsletter of the International Institute for FRP in Construction

Vol. 15, No. 1, March, 2018

IIFC has a new email address:
IIFC@IIFC.ORG
and a new website:
WWW.IIFC.ORG

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Dear members of the IIFC,

First of all, the organizing committee of the conference CICE 2018 presents you its best wishes for this new year 2018.

We inform you that 340 abstracts have been submitted to the Conference and we have received more than 225 papers to date. Paper revisions are scheduled for March 15, and authors will be informed of the result as soon as the revised manuscript is received. The Conference has received the support of the companies Freyssinet, D-measures, Mettler Toledo as well as the support of the French University association AUGC. If you would like to sponsor the conference or if you have any questions do not hesitate to contact the organising committee on cice2018@univ-lyon1.fr.

A selection of 4 keynote speakers was made by the organizing committee and validated by the Executive Committee of the IIFC. Three have currently agreed, namely, Larry Bank, Jian Guo Dai and Samuel Durand. The titles of their talks will soon be posted on the conference website:
Http://www.cice2018.com/en/pages/cice-2018-home.

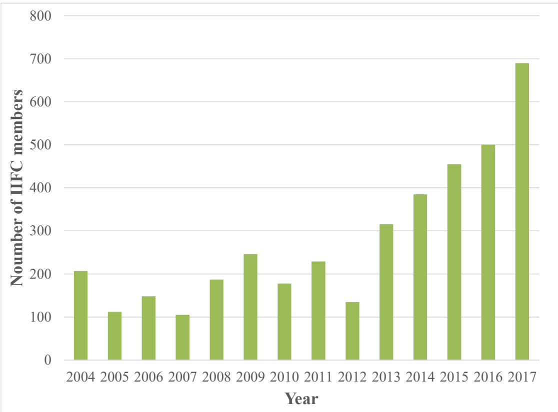
Emmanuel Ferrier, Karim Benzarti, Jean François Caron

President's Message

Dear IIFC members and readers of FRP International,

Welcome to the first issue of FRP International in 2018, our fifteenth year of publication!

As IIFC moves from strength to strength, I would like to express thanks for the contributions of the members of the Advisory, Honours, and Executive Committees, Council members, and all our members. Membership has grown to almost 700 in the last few years as shown in the figure below. Because of our steady growth and healthy financial status, the IIFC Council decided to halve the membership fees to $50 ($12.5 for student members) per annum in its last meeting in December 2016 in Hong Kong, effective from 2019. That is, the membership fees collected at CICE2018 will cover your membership fees for both 2019 and 2020.



Through extensive discussions within the IIFC and between the IIFC and FRPRCS Committee, it is my pleasure to report that the IIFC has taken over the responsibility of overseeing the management of the FRPRCS conference series. The benefits of integrating FRPRCS with IIFC are several fold, namely (i) optimal scheduling of conference times and locations that consider other well-established conference series, (ii) coordination of FRPRCS in odd numbered years with IIFC's major CICE conference in even numbered years, and (iii) utilisation of IIFC's resources to ensure the longevity of FRPRCS. The FRPRCS name will not change and FRPRCS will be run in conjunction with an ACI convention every 6th year (i.e. FRPRCS-16 ACI 2023…). Calls for proposals for hosting FRPRCS-14 (to be held in 2019) as well as CICE2022 (to be held in 2022) will be announced soon.

The IIFC has run the APFIS regional conference series in odd numbered years since 2007. As it has taken over the FRPRCS series, the APFIS conference series will be released from the IIFC and returned to its initiator (Prof. Scott Smith) who intends to form a regional committee to oversee the conference series in the future. The IIFC will continue to sponsor this series.

Many of you will remember that the IIFC set up a best PhD thesis competition with the first award given at CICE2016 in Hong Kong. This will continue at CICE2018 in Paris and it is anticipated that the IIFC will be able to provide partial travel assistance for the shortlisted candidates. Details of nomination can be found in this issue of the Newsletter.

Once again, the IIFC will present the IIFC Medal and the Distinguished Young Researcher award in Paris. IIFC members and Fellows are invited to nominate candidates for these two awards. Details of the nomination can also be found in this issue of the Newsletter.

The existence and growth of the IIFC is due to the active participation and contribution of its members. One of the many different ways to contribute to the IIFC is to share your research and other FRP related news through articles and news in this Newsletter. All members are encouraged to do this by contacting the Editor of the Newsletter, Dr Tao Yu at taoy@uow.edu.au.

I look forward to seeing most, if not all, of you at CICE2018 in Paris in July 2018!

Yours sincerely

Jian-Fei Chen

President of the IIFC

Call for Nominations for the

IIFC Medal and IIFC Distinguished Young Researcher Award

The IIFC Council decided in May 2006 that it would make the following two awards every two years at the CICE Conference: "The IIFC Medal" and "The IIFC Distinguished Young Researcher Award". The IIFC Honours Committee now calls for nominations for these awards which will be presented at the next official IIFC conference, CICE 2018 in Paris, France in July 2018.

All IIFC members are invited to nominate appropriate candidates for these awards by ***21 March 2018.*** Nominations should be forwarded to the IIFC Honours Committee through the Secretary of the IIFC Executive Committee, Professor Raafat El-Hacha, at relhacha@ucalgary.ca. Please use the special nomination forms.

The IIFC Medal

To be awarded to an IIFC member who has made distinguished contributions to the field of FRP composites for construction through research, practical applications, or both. One medal is awarded every two years. The winner will be invited to give the IIFC Distinguished Lecture at the next CICE conference.

Each nomination should consist of the following materials, which should be submitted electronically:

(1) A statement from the nominee confirming that he/she is willing to be nominated for the IIFC Medal and, if selected, to accept the Medal in person and to deliver the IIFC Distinguished Lecture at the forthcoming CICE conference;

(2) A detailed CV of the nominee;

(3) A summary of the nominee's achievements and contributions in the field of FRP composites in construction, which must include a) research output (e.g. a list of archival journal publications, conference papers, book chapters and books); b) evidence of impact (e.g. citations, impact on design standards and guidelines, and impact on engineering practice); c) significant contributions to the field of FRP structures and materials; d) contributions in promoting IIFC's aim and objectives and how he/she would continue to do so in the future;

(4) A list of 3 nominators. The nominators need to be IIFC Members or Fellows;

(5) A nominators' statement outlining the reasons for the nomination.

IIFC Distinguished Young Researcher Award

To be awarded to an IIFC member not older than 40 years of age at CICE 2018, who has distinguished himself/herself from his/her peers through research contributions in the field of FRP composites for construction. One award is given every two years. The winner will be invited to deliver one of the keynote lectures at the next CICE conference.

Each nomination should consist of the following materials, which should be submitted electronically:

(1) A statement from the nominee confirming that he/she is willing to be considered for the Award and, if selected to receive the Award, will accept the Award in person and to deliver a keynote lecture at the forthcoming CICE conference;

(2) A detailed CV of the nominee;

(3) A summary of the nominee's achievements and contributions in the field of FRP composites in construction, which must include a) research output (e.g. a list of archival journal publications, conference papers, book chapters and books); b) evidence of impact (e.g. citations, impact on design standards and guidelines and impact on engineering practice); c) a list of 10 career-best publications and their significance/contributions to the field of FRP structures and materials; d) contributions in promoting IIFC's aim and objectives and how he/she would continue to do so in the future;

(4) A list of 3 nominators. The nominators need to be IIFC Members or Fellows;

(5) A nominators' statement outlining the reasons for the nomination.

IIFC Best PhD Thesis Award

In order to promote high-quality research on FRP composites for construction, in 2016 the IIFC established the Best PhD Thesis Award which is to be awarded in association with the Composites in Civil Engineering (CICE) conference series. The inaugural Award was awarded at CICE 2016 in Hong Kong.

Using the CICE cycle, all PhD theses completed within two years of the application deadline are eligible for the award. To be eligible, theses must be nominated by a faculty member from the student's department (typically their advisor) who is a member of the IIFC. The nomination package shall include the following:

(1) Nominee's name, affiliation and contact information;

(2) Nominator's name, affiliation, contact information and relationship to nominee;

(3) Nominator's statement (2 pages) justifying the significance of the dissertation, novelty, research achievements, and scientific or practical contributions;

(4) 4-5 page 'extended abstract' summary of the thesis ***prepared by the nominee***.

Nominated theses making a 'short list' will be invited to give a presentation at a special session of the CICE conference. The Award Panel will select the Best PhD Thesis based on an evaluation of the nomination package and presentation made at CICE.

The winner will receive a certificate, $1000 (USD) and a two-year complimentary membership to IIFC. The winner will also be expected to prepare an article for *FRP International*.

The second Best Thesis Award will be awarded at CICE 2018 in Paris, France.

These submitted in calendar year 2016 or after, but was not nominated in the 2016 round, are eligible for the award in this round.

Nominations for the 2018 IIFC Best PhD Thesis Award should be submitted to Tao Yu (taoy@uow.edu.au) before 1 April 2018.

More information on the Award may be obtained from Tao Yu (taoy@uow.edu.au).

IIFC on LinkedIn

The IIFC Executive Committee from now will maintain an active LinkedIn page http://www.linkedin.com/company/iifc, posting relevant information such as events, conferences, webinars, newsletters, awards and relevant projects, both from the academia and the industry. All readers are invited to follow the IIFC LinkedIn page.

2018 IIFC Photo Competition

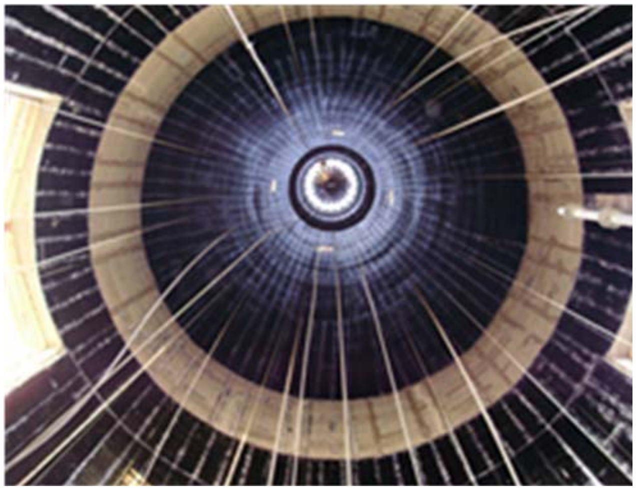
Have your photograph displayed in Paris!

Following remarkable participation and success at CICE 2005 and CICE 2012, IIFC, in celebration of its 15th year, is once again sponsoring the IIFC Photo Competition for CICE 2018 in Paris (http://www.cice2018.com).

Photos capturing any aspect of the use of FRP materials in construction (including research, production, fabrication, construction and completed structures) are welcome in the following categories:

(a) FRP in an engineering project (under construction or complete);

(b) FRP in a research study.



2012 Winning Entry

Seismic Strengthening of Concrete Chimney using FRP

Structural Technologies LLC, USA

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

Only photographs taken since July 2012 may be entered. Only three submissions are permitted from each photographer. Photos may be submitted by individuals, companies or organisations. Entries will be judged based on aesthetic merit by a panel of esteemed (and quite talented photographer) judges.

Winning entries in each category will also receive a $US250 award. Winning entries and all those receiving honorable mention will be displayed at CICE 2018 and be displayed prominently at iifc.org. **Only digital photographs will be accepted.** Colour or black-and-white are accepted. Photographs must be submitted in **JPG format** at the CICE 2018 Paper Submission Website (registration at site is required).

https://cice2018.sciencesconf.org/

(1) In the "Title" field, please enter the photo title.

(2) Select "2018 IIFC Photo Competition" in the "Type" field.

(3) Enter photographer affiliation in "Author" section as required.

(4) Upload entry details form as "Paper"

(5) Upload JPG version of photo as "Supplemental Data".

Entries not containing all required information will not be considered in the competition.

By submitting a photograph to the competition the entrant: (i) Attests that he/she is the person who took the photograph, (ii) Gives permission (with due acknowledgement) to the IIFC to use the photograph in publications, literature, and web sites.

Deadline for Entries is 1 April 2018

Advances in Standards/ Guidelines

Standard Specification for GFRP Bars Published by ASTM

by Prof. Charles E. Bakis and Prof. Russell Gentry

ASTM D7957/D7957M-17, Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement has been published in Vol. 15.03 of the American Society for Testing and Materials (ASTM) Book of Standards in August 2017.

The standard was developed by ASTM Subcommittee D30.10 on Composites for Civil Structures, in cooperation with American Concrete Institute Subcommittee 440K on Fiber Reinforced Polymer Material Characteristics. The specification covers glass fiber reinforced polymer (GFRP) bars, provided in cut lengths and bent shapes and having external surface enhancement for concrete reinforcement. E-glass fibers and vinylester matrix materials are permitted. Property limits and test methods for qualification of bars include glass transition temperature, degree of cure, measured cross-sectional area, ultimate tensile force, tensile modulus of elasticity, ultimate strain, transverse shear strength, bond strength, moisture absorption, and alkaline resistance. For bent bars, minimum bend diameters are prescribed and qualification includes the ultimate tensile force of the bent portion of the bar. Property limits and test methods for quality control and certification include fiber mass content, glass transition temperature, degree of cure, measured cross-sectional area, ultimate tensile force, tensile modulus of elasticity, ultimate tensile strain, and moisture absorption. Also provided are requirements for sampling, rejection, product certification, and markings/traceability. Inch-pound and SI units are applicable as specifications D7957 and D7957M, respectively.

A copy of the complete standard may be obtained from ASTM, www.astm.org.

Publication of the Prospect for New Guidance in the Design of FRP Structures

by Prof. Luigi Ascione

The topic of FRP structures has been included, for the first time, in the Mandate M/515 of the European Community (EC) for the development and publication of the second generation of EN Eurocodes.

In the beginning of 2016, the Joint Research Centre published the Prospect for New Guidance in the Design of FRP Structures (JRC99714, EUR 27666 EN), prepared by the Working Group No. 4 (WG4) of the Technical Committee 250 of the European Committee for Standardization (CEN/TC 250), chaired by Prof. Luigi Ascione.

From January 2016 to July 2016, the document has been subjected to a public inquiry by the European National Standardization Bodies (NSBs). Based on the comments/suggestions sent by the NSBs, a revised version of the document was prepared, which was recently published by the Association of the European Composites Industry (EuCIA). Recently, in July 2017, the EC has approved a new work item consisting in the adaptation of the document into a CEN Technical Specification. This is the second step on the road towards the publication of a Structural Eurocode (Third Step).


First Regional Meeting on the Use of GFRP in Construction

Organized by the FRP Group of the Center of Study of Tropical Construction and Architecture (CECAT). Slowly but firmly, new construction materials are gaining importance in many applications. This is coupled with a more general trend related to a technological revolution, commonly named as the revolution of the materials' science. This movement is strengthened by architects, engineers and scientist, who are constantly trying to develop new materials for specific purposes. To this end, in construction, the use of Fiber Reinforced Polymers (FRP) has increased significantly due to its high strength, low weight, ease of use and most importantly, its lack of corrosion in aggressive environments. It is known that the main issue of steel reinforced concrete (RC) structures is the corrosion of the steel; therefore, since the 80s, in many countries of our region, FRP reinforcement has started to be used in lieu of steel to avoid the corrosion mainly created by the high chloride content in costal zones. The objectives of this first meeting are:

1. Share with designers, owners and constructors the characteristics and numerous advantages of the use of FRPs as reinforcement in RC structures.
2. Exchange experiences and discuss about the economic impact and the durability of concrete structures reinforced with FRP.

Thematic areas:

1. Design of reinforced concrete elements with FRP
2. Use of FRP reinforcement in design of new concrete elements or for strengthening of existing structures: Use of bars or textiles.
3. Examples of case studies
   3.1-New construction
   3.2-Rehabilitation
4. Development of new materials and technologies

Coordinators:

Dr. Ing. Hugo Wainshtok Rivas (CUJAE)

Dr. Ing. Antonio Nanni (UM)

Ms C. Ing. Isel del Carmen Díaz (CUJAE)

Deadlines:

Send full paper for evaluation by July 30, 2018

Acceptance notification: August 20, 2018.

Reviewed document for modification will be sent by September 30, 2018.

For more information, contact the Organization Committee of the 4th CIIC:

Dra. Vivian Elena Parnás: vivian@civil.cujae.edu.cu

Dr. William Cobelo Tristá: wcobelo@civil.cujae.edu.cu.

Profs. Thomas Keller, Leif A. Carlsson and Yeoshua Frostig (ICSS-12 Chairs)

We are pleased to invite you to participate in the 12th International Conference on Sandwich Structures (ICSS-12), which will take place in Lausanne, Switzerland from 19 to 22 August 2018.

ICSS-12 is organized by the EPFL Composite Construction Laboratory (CCLab). Following well-established tradition, the Conference will provide an international forum for researchers and practitioners to exchange ideas and recent advances regarding sandwich structures and materials in the fields of aerospace, automotive, mechanical, naval and civil engineering and architecture. An exhibition of sandwich products, technology, equipment and associated services will be presented at the Conference venue.

We look forward to meeting you in Lausanne in August 2018 at the ICSS-12 Conference.

Conference Topics

The Conference Program includes sessions on:

- Impact loading, Dynamics - Sandwich disbond

- Blast loading - Delamination - Fire resistance

- Fatigue, Fracture - Environmental influence

- NDE - Design - Materials - Modeling

-Manufacturing - Mechanics - Applications

Submission of Abstracts

Authors wishing to participate are invited to submit an extended abstract (2-3 pages) following the detailed instructions at the conference website https://icss12.epfl.ch/submissions.

Novartis Main Gate Building, Basel, Switzerland – Installation of GFRP-PUR sandwich roof, 2006.

Wilhelminakanaal, Tillburg, Netherlands – Installation of GFRP sandwich lock gates manufactured by FiberCore Europe, 2016 (image from www.aliancys.com)

Upcoming Events

International Association for Bridge and Structural Engineering (IABSE) Symposium http://www.iabse.org/IABSE/Events/Guimaraes_2019

The IABSE Symposium organised by the Portuguese Group of IABSE (Associação Portuguesa de Engenharia de Estruturas - APEE) in co-operation with the Institute for Sustainability and Innovation in Structural Engineering (ISISE), and the University of Minho, Portugal will be held on March 27-29, 2019.

9th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2018) http://www.cice2018.com/en

The 9th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2018) will be held in Paris, France on 17-19 July 2018. CICE 2018 will aims to provide 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 4th Brazilian Conference on Composite Materials http://bccm4.com.br/2018/

Welcome to BCCM4! The 4th Brazilian Conference on Composite Materials will be hosted by Pontifical Catholic University of Rio de Janeiro in Rio de Janeiro, Brazil, from July 22nd to 25th, 2018. It is the fourth event of a series of biannual international conferences on composite materials. BCCM4 is intended to bring together students, researchers from academia and industry to share and discuss recent developments in the field.

IIFC Webinar Update

IIFC's online seminars contain 16 videos on various topics, in 2017 these online webinars have been viewed 4085 times for a total of 7154 views. The YouTube Channel has 104 subscribers.

https://youtube/AMWziRZuWHk

IIFC WEBINAR 16 : Prestressed FRP for new constructions, Raafat El-HAcha, university of

de FRP CONSTRUCTION IIFC WEBINAR 56 vues il y a 2 mois

New webinars will be scheduled for the next semester, if you have a contribution or seminar proposal, please contact me quickly, just a presentation in Power point format and one to two hours of your time.

Thanks to all the participants.

Disseminate this information to promote the IIFC online webinars.

For more information: Ferrier Emmanuel, emmanuel.ferrier@univ-lyon1.fr

The following paper was awarded Best Paper for research on FRP strengthening existing structures at the APFIS 2017 held in Singapore in July 2017.

MOMENT-CURVATURE BASED MODELLING OF FRP-STRENGTHENED RC MEMBERS ANCHORED WITH FRP ANCHORS

Scott T. Smith[1], **Hayder A. Rasheed**[2] **and Seo Jin Kim**[3]

1. School of Environment, Science and Engineering, Southern Cross University, Lismore, NSW, 2480, Australia. scott.smith@scu.edu.au
2. College of Engineering, Kansas State University, Manhattan, KS 66506, USA. hayder@ksu.edu
3. Rondo Building Services Pty Ltd, Erskine Part, NSW, 2759, Australia. paul.kim@rondo.com.au

Abstract: Debonding of externally bonded fibre-reinforced polymer (FRP) composites in FRP-concrete bonded interfaces occurs in generally a brittle manner and at a level of strain well below the strain capacity of the FRP. The addition of anchorage devices can, however, enhance the strain capacity and deformability of the bonded interface. The proof of concept has been demonstrated in experimental studies over the years although there is much less development of modelling methods by comparison that address the full-range of response from initial loading to eventual interface and anchorage failure. This paper presents the details of a closed-form analytical model that enables the complete load deflection response of FRP flexurally-strengthened RC members that contain anchorage devices to be generated. The method relies upon establishing predefined moment-curvature expressions corresponding to key stages of the member behaviour.

Keywords: Anchors, Concrete, FRP, Modelling, Moment-Curvature

INTRODUCTION

The application of fibre-reinforced polymer (FRP) composites to the tension face of reinforced concrete (RC) flexural members offers an effective strengthening solution [1]. The FRP can, however, debond from the concrete substrate in often a sudden manner at a level of strain well below the capacity of the FRP. Anchorage devices though can increase the usable level of strain in the FRP and also increase the deformability of the strengthened member [2]. Anchors made from FRP (herein FRP anchors) have been shown specifically to be effective in FRP-strengthened concrete joints and slabs as well as other structural members [3]. In the case of flexural members, the plotting of the complete load-deflection response has been shown to be a convenient means to quantify and understand overall member behavior.

In comparison to experimental investigations, there has been a distinct lack of modelling investigations on FRP-strengthened RC members anchored with FRP anchors. In order to simulate the complete load-deflection response, recourse can be made to finite element analysis for example although such a method can be tedious, particularly when anchorage devices are considered. A convenient closed-form method that utilises predefined moment-curvature relationships is proposed herein. The method considers key stages of the member behaviour that include concrete cracking, yield of the internal steel tension reinforcement, and debonding of the FRP with the inclusion of anchorage devices. The real innovation of the method rests in the incorporation of anchorage devices and this particular aspect has remained relatively untouched by the research community to date. This paper reports the details of the closed-form model. It is an abridged version of a larger contribution on the topic as provided in Reference [4].

2. Model Details and Comparison with Test data

It has been observed in tests on FRP-strengthened slabs anchored with FRP anchors [3] that four distinct linear responses exists between load and deflection where the transition between each zone corresponds to (i) first concrete cracking, (ii) internal steel yield, and (iii) initiation of debonding. The end point corresponds to debonding failure (which can include anchor failure at times). The model reported herein is based upon a four stage moment-versus curvature relationship that can be applied along the whole length of the member. The so called quad-linear moment-curvature relationship in shown in Figure 1 where ϕ, M, E and I represent curvature, moment, elastic modulus and second moment of area, respectively. In addition, the subscripts cr, y, db, and f represent concrete cracking, steel yield, debonding, and failure. Subscript a refers to an arbitrary level or moment or curvature.

Figure 2 shows the variation of moment-distribution along a symmetrical half-length of slab under four-point bending where L represents each segment length. This figure is based on a beam failing by intermediate crack debonding that initiates beneath the load point. No account is made of the member behavior after complete plate debonding because the load enhancement provided by the FRP is lost.

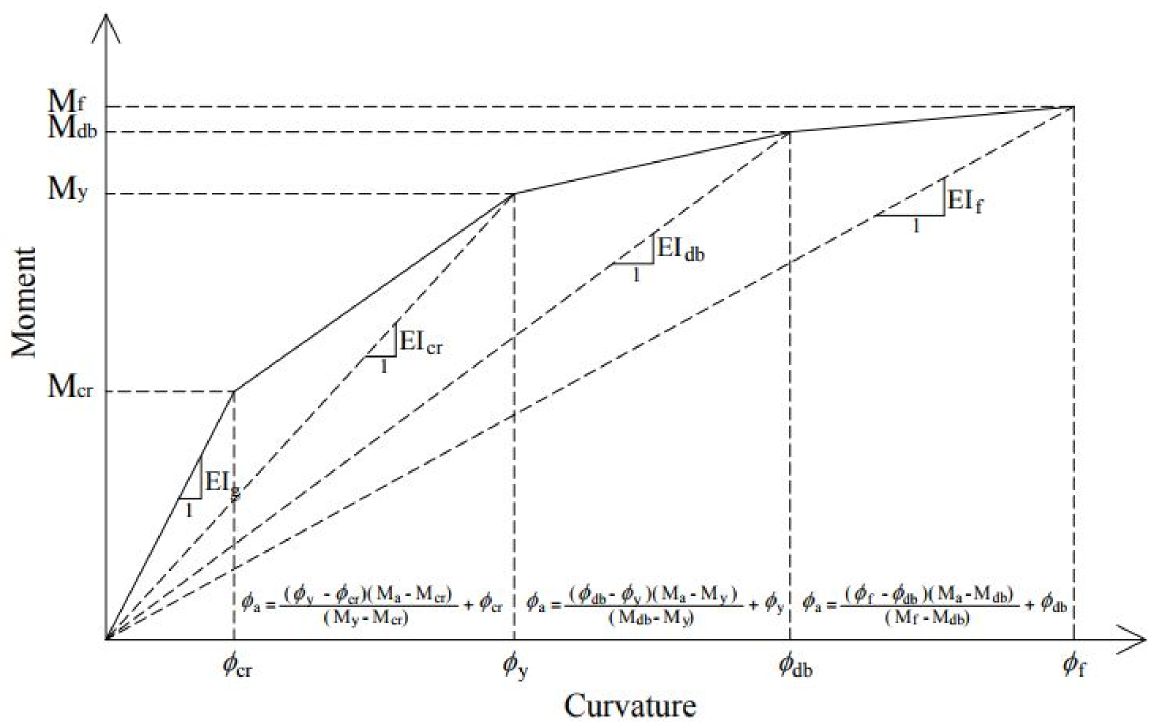


Figure 1. Assumed quad-linear moment curvature response

Closed-form equations then enable the four stages of the load-deflection response to be generated and equations are derived from the second-moment area method. In this case, the moment of the area of the curvature is integrated along the beam in discrete lengths. Solutions are then generated for each of the four stages for a simply-supported beam subjected to four-point bending.

They are provided herein:

Stage 1: Uncracked section ($0 < M_a < M_{cr}$)

$$\Delta_{mid\,(4-point)} = \frac{\emptyset_a}{24}(3L - 4L_a^2) \tag{1}$$

Stage 2: Cracked section ($M_{cr} < M_a < M_y$)

$$\Delta_{mid\,(4-point)} = \frac{\emptyset_a}{24}(3L - 4L_a^2) + \frac{(L_g+L_a)}{6}(\emptyset_{cr}L_a - \emptyset_a L_g) \tag{2}$$

Stage 3: Yielded section ($M_y < M_a < M_{db}$)

$$\Delta_{mid\,(4-point)} = \frac{\emptyset_a}{24}(3L - 4L_a^2) + \frac{L_y}{6}\left[\emptyset_{cr}(L_y + L_g) - \emptyset_a(L_y + L_a)\right] + \frac{\emptyset_{y(L_a-L_g)(L_a+L_g+L_y)}}{6} \tag{3}$$

Stage 4: Debonded section ($M_{db} < M_a < M_f$)

$$\Delta_{mid\,(4-point)} = \frac{\emptyset_a}{24}(3L - 4L_a^2) - \frac{\emptyset_a}{6}L_{db}(L_a + L_{db}) + \frac{[\emptyset_{db}(L_a-L_y)(L_a+L_{db}+L_y)]}{6} + \frac{\emptyset_{y(L_{db}-L_g)(L_a+L_g+L_y)}}{6} + \frac{\emptyset_{cr}}{6}L_y(L_y + L_g) \tag{4}$$

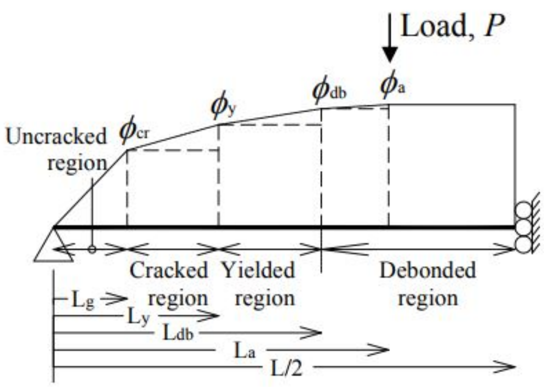


Figure 2. Full range of moment-curvature relationship for symmetrical half-slab

The reader can refer to Reference [4] for the calculations of M_{cr} (cracking moment), M_y (yield moment), and M_{db} (IC debonding moment) as the theory is well established. The respective curvatures can then be calculated from the moments. In addition, L_g, L_y and L_{db} can be calculated from M_{cr}/P, M_{db}/P and M_f/P. Explicit expressions are required for the calculation of Mf (ultimate curvature) and M_f (ultimate moment) as they need to consider debonding failure in the presence of FRP anchors. A unique relationship is needed for each given the curvatures and moments are found to be dependent on the number of anchors and their arrangements. The relationship also needs to reflect the loss of member stiffness upon the initiation of debonding. The general solution for the predicted ultimate curvature at failure is therefore given as follows:

$$\emptyset_f = \emptyset_{db} + \emptyset_{inc} \times number\ of\ anchors\ in\ shear\ span \tag{5}$$

where ϕ_b is the calculated debonding curvature (back-calculated from calculated M_{db}) while ϕ_{inc} is the average curvature increment per anchor over the range ϕ_f - ϕ_{db} where ϕ_f is back-calculated from the test failure moment. The following power equation is established (R^2=0.9755) which is based on a regression analysis of the difference between the predicted debonding moment and the experimental ultimate moment for a series of test slabs [3] containing varying anchor types and locations:

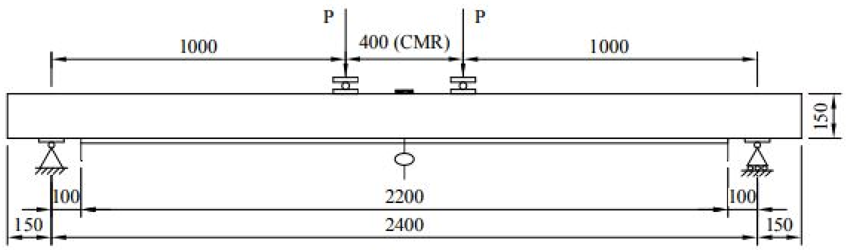
$$M_f = M_{db} + 3\times10^{-8} \times (total\ anchor\ fiber\ shear\ area)^{3.6683} \tag{6}$$

where the total anchor fiber shear area refers to a shear span. In order to demonstrate the application and accuracy of the method, Slab S5 from Reference [3] is investigated. A brief explanation of the test is firstly provided. Figure 3a shows an elevation of an FRP-strengthened slab subjected to four-point bending. Figure 3b is a view of the FRP plate and it shows FRP anchors of constant fibre content evenly distributed within the shear span regions.

The predicted debonding curvature Mdb is 5.2120E-05 mm-1 while the experimental ultimate curvature

Mf is 9.7527E-05 mm-1. The curvature difference Mf-Mdb is therefore 4.5407E-05 mm-1. As there are four anchors, the curvature increment per anchor ϕ_{inc}

is 1.1352E-05 mm-1. In terms of application of Equation 6, the fibre cross-sectional area per anchor is 41.5 mm2 while the predicted debonding moment M_{db} = 21.67 kNm. The calculated moment at failure is therefore 25.85 kNm while the experimental ultimate moment is 25.90 kNm. Figure 4 shows the predicted and experimental load versus deflection responses. The close match overall and for each of the four stages is evident. In addition, experimental and predicted ultimate loads are closely matched at 51.80 kN and 51.70 kN, respectively, while the corresponding deflections are 41.99 mm and 41.95 mm.



(a) Elevation

(b) FRP anchor arrangement (dotted lines indicate extent of constant moment region)

Figure 3. Slab details and FRP anchor arrangement.

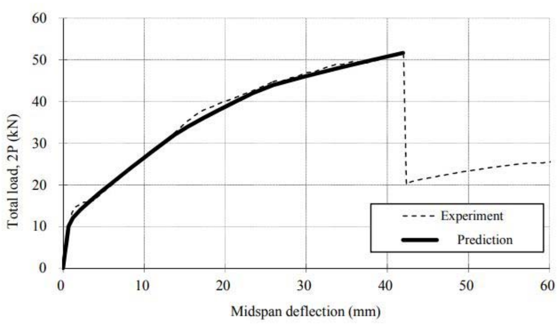


Figure 4.Predicted and experimental load-versus displacement response for Slab S5.

CONCLUSIONS

This paper has presented the details of a model that enables the complete load-deflection response of FRP-strengthened RC slabs anchored with FRP anchors to be calculated. The model is based upon a four-stage predefined moment-curvature relationship and expressions for the ultimate curvature and moment are calibrated from test data. While the results are specific to the tests available under investigation, a methodology has, however, been established that can be exploited in future studies. The methodology will also enable larger test databases to be established and analysed in a systematic manner. The ultimate goal with this research is to establish generic expressions for the ultimate curvature and moment that consider the influence of anchorage devices.

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[1] H.A. Rasheed. Strengthening Design of Reinforced Concrete with FRP. CRC Press, 2015.

[2] R. Kalfat, R. Al-Mahaidi, R. and S.T. Smith. Anchorage devices used to improve the performance of concrete structures retrofitted with FRP composites: A-state-of-the-art review. Journal of Composites for Construction, 17(1):14-33, 2013.

[3] S.T. Smith, S. Hu, S.J. Kim, and R. Seracino. FRP-strengthened RC slabs anchored with FRP anchors. Engineering Structures, 33(4):1075-1087, 2013.

[4] S.T. Smith, H.A. Rasheed, S.J. Kim. Full-range load-deflection response of FRP-strengthened RC flexural members anchored with FRP anchors. Composite Structures, 167:207-218, 2017.

The following is an extended abstract of the PhD thesis completed by Tien-Thuy NGUY at University of Warwick, the Runner-up of the IIFC Best Thesis Competition at the CICE 2016 conference.

LATER-TORSIONAL BUCKLING RESISTANCE OF PULTRUDED FIBRE REINFORCED POLYMER SHAPES

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1. INTRODUCTION

Pultruded Fibre-Reinforced Polymer (PFRP) is a modern construction material, produced by a continuous composite material process called "pultrusion". This is a cost-effective process suitable for the production of a wide range of structural uniform thin-walled cross-sections used in frame construction. PFRP shapes consist of thin walls of glass (or carbon) fibre reinforcement embedded in a thermoset resin based matrix. Applications in civil engineering works are growing because of the distinct advantages over the conventional materials such as: lightweight, high fatigue resistance, high corrosion resistance and electromagnetic transparency.

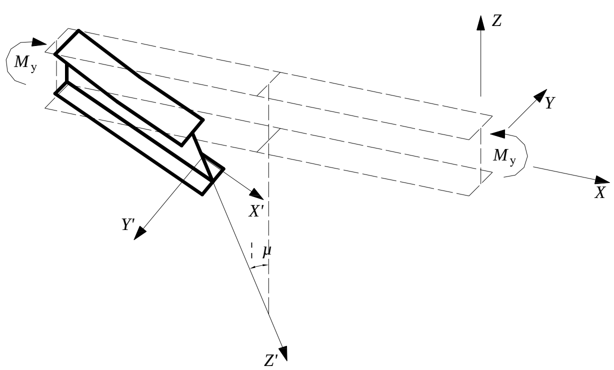


Figure 1. Lateral-torsional buckling of a simply supported I- beam under pure bending.

Lateral-Torsional Buckling (LTB) is a mode of ultimate failure (as illustrated in Figure 1) that occurs when a laterally unrestrained thin-walled open-shaped beam is subjected to flexure about the major axis. This linear elastic failure is characterised by a coupled elastic deformation of lateral deflection and twist rotation about the beam's longitudinal centroidal axis. Previous studies on the LTB response of PFRP beams, especially by way of physical testing, are limited and lacking in physical rigor.

The nominee's PhD work had the aim of furthering our understanding of the LTB resistance of PFRP I- and channel beams under various loading and displacement boundary conditions by way of nonlinear Finite Element Analysis (FEA) [1] and physical testing [2], thereby leading to the construction of a design curve with universal application [3] that contributes to the development of a future Eurocode for FRP materials.

2. EXPERIMENTAL INVESTIGATION

The research programme included material characterization and lateral-torsional buckling testing. Determined are the four elastic constants of the: Longitudinal modulus of elasticity; Transverse modulus of elasticity; in-plane shear modulus of elasticity; Major Poisson's ratio. These constants are used in theoretical predictions, nonlinear numerical simulations by Abaqus®, and in the calibration process for a design curve for PFRP members in flexure. and are determined by coupon tests on the respective direction based on a total number of 74 tests (54 in Longitudinal and 20 in Transverse direction). Longitudinal tests adopted bidirectional strain gaging to determine the complementary Poisson's ratio. To determine, tensile testing was conducted using a straight-sided coupon with the roving fibre orientation having 10o offset to the longer-sides, as shown in Figure 2(a). This arrangement induces a biaxial stress state that consists of the three in-plane stresses when the coupon is subjected to axial tension. These stresses are established using a rosette (tri-directional) strain gauge. Adopting strain transformations the Principal shear stress and strain are calculated, from which is predicted, using the approach shown in the plot in Figure 2(b).

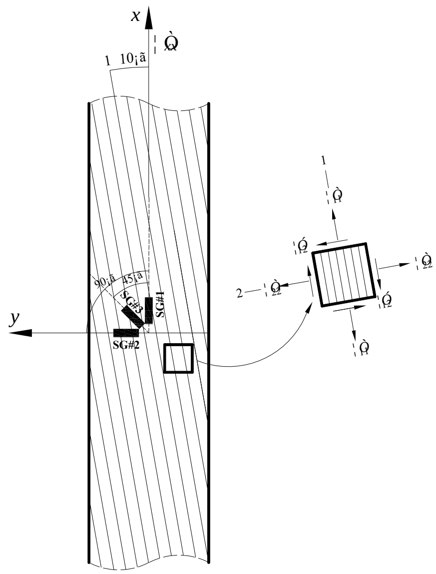


Figure 2(a). Specimen for 10 degree off-axis test.

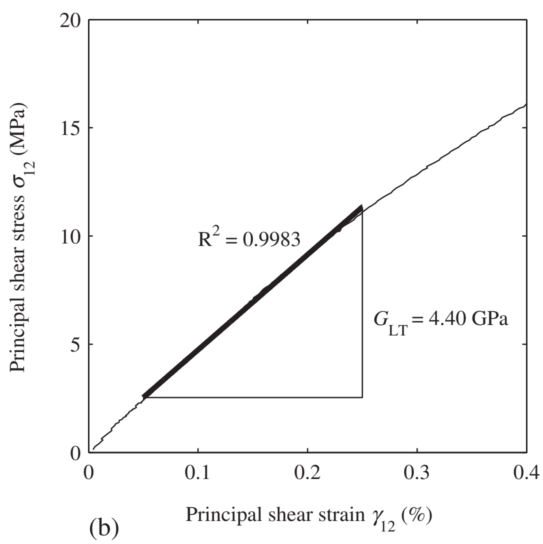


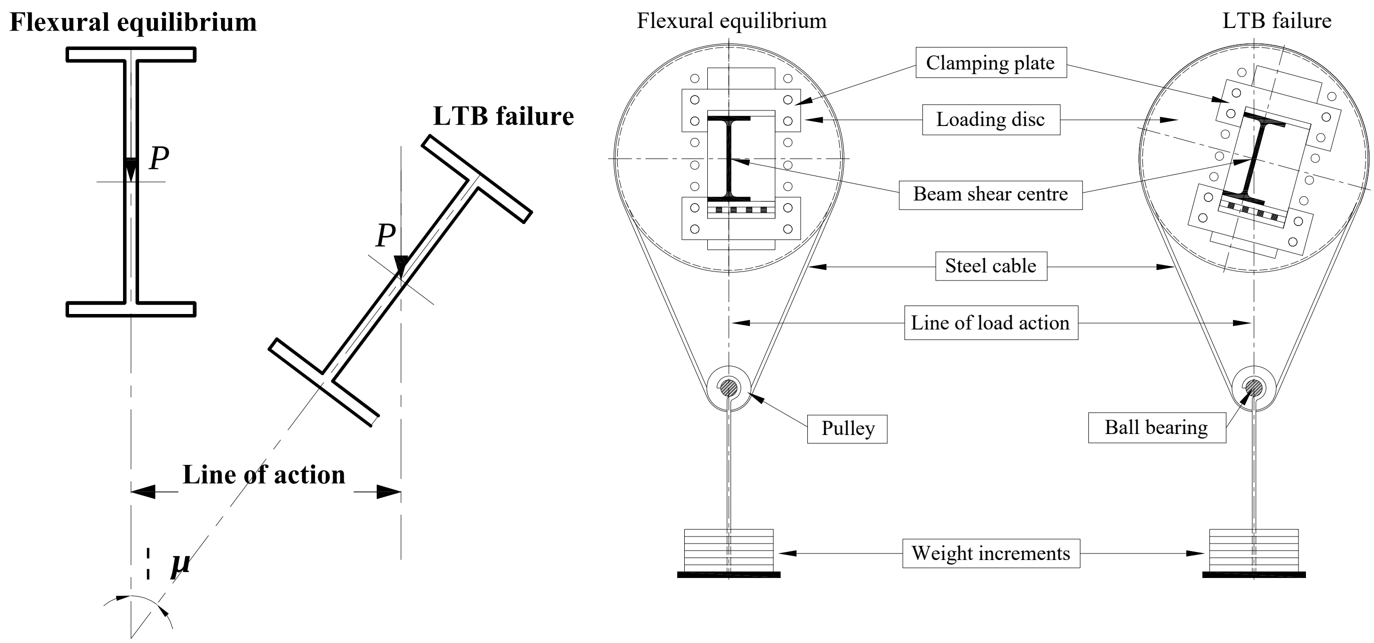
Figure 2(b).Typical shear stress-strain.

The material testing revealed that and are significantly higher (27% to 43% for; 40% to 60% for) than those given in the pultruder's design manual (Fiberline Composites). The results also showed a 13% difference for in the two flanges of the outstands of the I-section. The 10o off-axis testing gave consistent values for in a range of 4.2 to 4.8 GPa. The 10o off-axis tensile coupons are easy to prepare and the test set-up is simple comparing to other ASTM standards. In this PhD work it was recommended that the 10o off-axis test method is the most suitable for characterizing of PFRP material.

To simulate the desired LTB response it is essential that load positions remain unchanged when the member goes unstable, and their line of actions remain parallel to the undeformed member shape. This assumed failing deformation is shown in Figure 3(a). Previous experimental studies failed to satisfy these boundary conditions precisely and so the LTB resistances reported are not always reliable. The experimental weakness is overcome by using gravity loading in a three-point bending configuration, as presented in Figure 3(b). This configuration allows for a variation in the vertical loading point (from top to bottom flange of beam) by moving the two pairs of clamping plates to align the disc position vertically until its horizontal centreline coincides with the top or bottom flange level, and so the resistance at a height for top or bottom flange can be obtained.

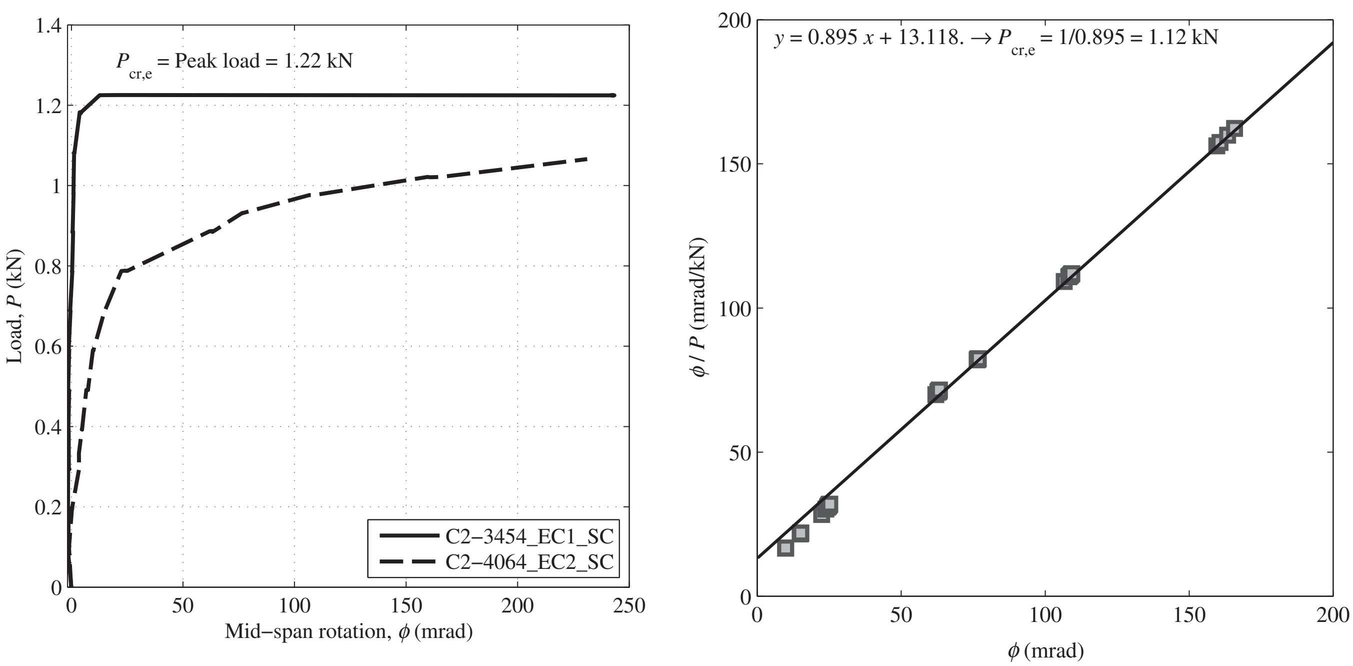
The nominee conducted 114 individual tests on 19 beam specimens having two displacement end conditions and at three load heights for top flange, shear centre and bottom flange. The experimental buckling load is established with 'peak' load (solid curve in Figure 4(a)) or Southwell plot methods (dashed line in Figures 4(a) and 4(b)), depending on the load–mid-span rotation response.

The poor compatibility between the hydrophilic fibers and hydrophobic polymers has been discussed in many researches [6-8], but is still difficult to improve without heavy chemical treatment. Moreover, elementary flax fibers are made of concentric walls containing numerous cellulosic microfibrils, embedded in a pectic and hemicellulosic matrix. In the thickest wall (S2) microfibrils are oriented at 10° with the fiber axis. This complex structure lead to a non-linear tensile behavior, described in the literature with a higher slope at small followed by softening of the curve into a second linear part [4,9].



(a) (b)

Figure 3. (a) LTB theoretical loading requirements; (b) schematic set-up of the loading fixture.



(a) (b)

Figure 4. (a) Two typical LTB failures; (b) Southwell plot with test data from C2_4064_EC2_SC.

By substituting the EL and GLT values reported in the pultruder's design manual into closed-form equations for LTB resistance it was found that the test results are all significantly higher than predicted.

This shows that by choosing the pultruder's tabulated 'design' properties the closed-formed equations will give an LTB design resistance that is safe. By making a comparison between test results and predictions for the I-section using the measured moduli of elasticities, the test method is proven to perform most satisfactorily and shown to give reliable resistances at different load height positions. The differences between testing and theory are due to the inherent displacement boundary conditions in the experimental set-up. The level of influence on failure load of the experimental restraint from the assumed 'free' warping restraint, however, remains unknown. Although the combination of material, geometric and loading imperfections might have had a significant effect on the LTB resistance, this was not found to be so [1-2].

3. FINITE ELEMENT INVESTIGATION

The LTB response of PFRP beams subjected to a point load at mid-span is investigated using nonlinear finite element analysis by Abaqus® [1]. The initial out-of-straightness imperfection is measured from the 19 test beams and is introduced into the beam's mesh by modifying the nodal coordinates through the adoption of a vector field. The modified shapes are obtained by scaling the first eigenvalue buckling mode shape for Euler buckling of a perfectly straight concentrically loaded column. The plates of the shape are treated as single layered transverse isotropic materials adopting the 8-noded thick shell element (S8R). To model the cross-section the fillet areas at flange-web junctions are taken into account by assigning 'over-thickness' elements.

Nonlinear analyses, considering the influence of initial out-of-straightness geometric imperfection, are carried out. This imperfection is introduced [1] into the FE model as a half sine wave shape with the maximum magnitude located at mid-span. Comparison between FE nonlinear analyses and test results are made using a limiting buckling load, which is defined as the load when mid-span rotation reached 3 degrees. This approach is needed because the load-displacement responses do not show a clear bifurcation due to the presence of imperfections. It is important to know that a combination of geometric and material imperfections might create a test condition where the beam has a much higher resistance than when the testing possesses no geometrical imperfection.

For the calibration of M sensitivity analyses are implemented against five key parameters. These investigations showed that: (1) it is necessary to take into account the fillet radius areas when analysing LTB failure; (2) the characterization of is highly important for the LTB problem since it has a relatively high effect on LTB resistance; (3) the LTB response is sensitive with the change in geometric imperfection. In the PhD thesis the nominee makes the case that the allowance for the initial out-of-straightness imperfection in ASTM D3917 of (L is the span) is too high and not appropriate, while the equivalent allowance in BS EN 13706 of is a more suitable practical limit for this tolerance in the pultrusion process; (4) a beam's response is significantly influenced by the lateral position of the vertical loading. The FE investigations have shown that for an eccentricity of 3 mm, the LTB resistance is reduced by up to 17% or increased by up to 19%; (5) the influence of vertical load height is more significant when material is of PFRP than of steel.

4. DESIGN PROPOSAL FOR PFRP BEAM IN BENDING

The unique test series is used to calibrate the design procedure to evaluate LTB resistance as shown in Figure 5. The design procedure is based on the Eurocode 3 (EN 1993-1-1:2005) approach for structural steel uniform members in bending. The calibration follows the standard approach given in Eurocode 0 (EN 1990:2002). To be specific in terms of formulae and calibration values the nominee recommends a plateau length $\bar{\lambda}_{\mathrm{LT.0}}$ of 0.5 and an imperfection factor α_{LT} of 0.34. The partial factor γ_{M} is calibrated to lie between 1.14 -1.19 for an I-section and 1.16 to 1.18 for the three C-sections.

To take into account of the level of uncertainty in the measured geometries and failure load test results, and the underlying assumptions made, the nominee is confident to recommend that γ_{M} is 1.3 for the sections studied in the research work.

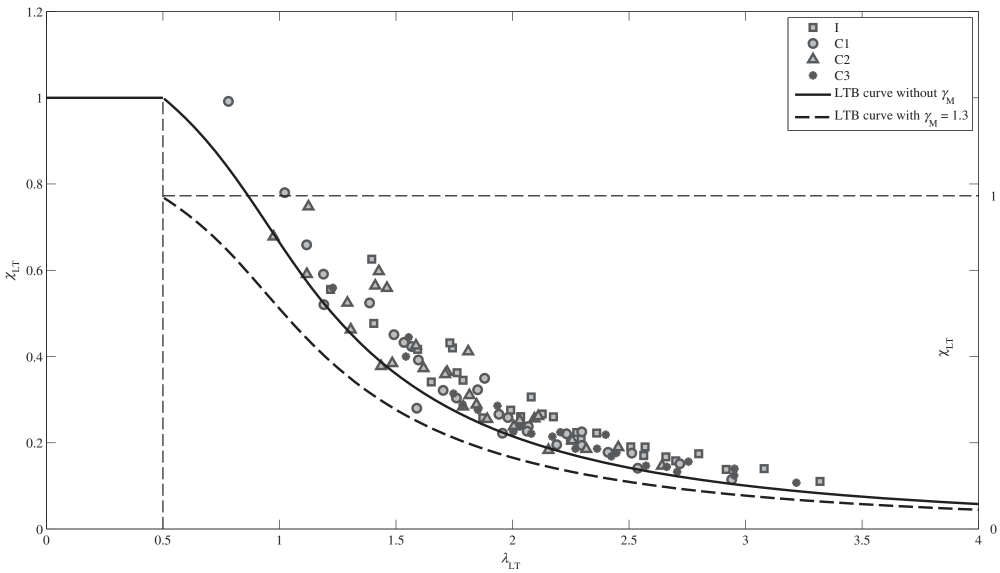


Figure 5. LTB curves for PFRP beams

5. PUBLICATIONS

This PhD research has provided information to produce the following journal articles:

[1] TT Nguyen, TM Chan, JT Mottram (2013). Influence of boundary conditions and geometric imperfections on lateral-torsional buckling resistance of a pultruded frp I-beam by FEA. Composite structures 100,233-242.

[2] TT Nguyen, TM Chan, JT Mottram (2014). Lateral-torsional buckling resistance by testing for pultruded frp beams under different loading and displacement boundary conditions. Composite part B: Engineering 60, 306-318.

[3] TT Nguyen, TM Chan, JT Mottram (2015). Lateral-torsional buckling design for pultruded frp beams. Composite structures 133, 782-793.

And the following conference papers:

[1] TT Nguyen, TM Chan, JT Mottram (2012). Coupled buckling of simply supported fiber reinforced polymer I-beams: A finite element parametric study. In Proceedings of CIMS2012 Conference, Glasgow, UK, 407-414.

[2] TT Nguyen, TM Chan, JT Mottram (2013). Experimental determination of the resistance of pultruded FRP beams failing by lateral-torsional buckling, In Proc. 6th Inter. Conf. on Advanced Composites in Construction, NetComposites Ltd., Chesterfield, UK, 2013, 252-263.

This Ph.D thesis was also used to inform the writing of the Eurocodes Scientific and Technical Report "Prospect for New Guidance in the Design of FRP - Support to the implementation, harmonization and further development of the Eurocodes" by L. Ascione, J-F. Caron, P. Godonou, K. van IJselmuijden, J. Knippers, T. Mottram, M. Oppe, M.G. Sorensen, J. Taby, L. Tromp; Editors: L. Ascione, E. Gutierrez, S. Dimova, A. Pinto, S. Denton.

http://eurocodes.jrc.ec.europa.eu/showpublication.php?id=539

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Part D: Extended abstract prepared by the nominee
Please attach a 4- or 5-page "extended abstract" summary of the thesis to the form.

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