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FRP composites in structures: some recent research

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Abstract

An on-going research programme led by the first author at The Hong Kong Polytechnic University (PolyU) has addressed many issues in the application of fibre-reinforced polymer (FRP) composites in civil engineering structures. While the main focus of the programme has been on the behaviour and modelling of reinforced concrete (RC) and metallic structures strengthened with bonded FRP reinforcement, increasing attention has also been devoted to the use of FRP composites in new construction. This paper presents a brief summary of some of the latest advances of the research programme, covering the strengthening of RC structures with bonded FRP reinforcement, seismic retrofit of RC structures, durability of FRP-strengthened RC structures, hybrid FRPconcrete structures, and smart FRP structures. Much of the work has involved collaboration with the third author at the University of Edinburgh.

Keywords

frp, research, recent, structures, composites

Disciplines

Engineering | Science and Technology Studies

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FRP COMPOSITES IN STRUCTURES: SOME RECENT RESEARCH

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ABSTRACT

An on-going research programme led by the first author at The Hong Kong Polytechnic University (PolyU) has addressed many issues in the application of fibre-reinforced polymer (FRP) composites in civil engineering structures. While the main focus of the programme has been on the behaviour and modelling of reinforced concrete (RC) and metallic structures strengthened with bonded FRP reinforcement, increasing attention has also been devoted to the use of FRP composites in new construction. This paper presents a brief summary of some of the latest advances of the research programme, covering the strengthening of RC structures with bonded FRP reinforcement, seismic retrofit of RC structures, durability of FRP-strengthened RC structures, hybrid FRP-concrete structures, and smart FRP structures. Much of the work has involved collaboration with the third author at the University of Edinburgh.

KEYWORDS

FRP, RC structures, Strengthening, Seismic retrofit, Durability, Smart structures

INTRODUCTION

The application of fibre-reinforced polymer (FRP) composites in civil engineering structures has become an important area of engineering research. At The Hong Kong Polytechnic University (PolyU), extensive research has been conducted in this area; most of the work undertaken prior to 2002 was summarised in Teng et al. (2002). The present paper discusses recent progress of the research programme.

While the main focus of the programme at PolyU has been on the behaviour and modelling of reinforced concrete (RC) and metallic structures strengthened with bonded FRP reinforcement, increasing attention has also been devoted to the role of FRP composites in new construction. This paper provides a brief summary of the latest advances of the research programme in the following areas: strengthening of RC structures with bonded FRP reinforcement; seismic retrofit of RC structures; durability of FRP-strengthened RC structures; hybrid FRP-concrete structures; and smart FRP structures. Much of the work has involved collaboration with the third author at the University of Edinburgh.

RC STRUCTURES WITH EXTERNALLY BONDED FRP REINFORCEMENT

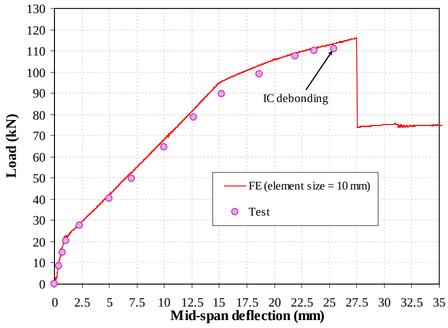
Numerical modelling of FRP-strengthened RC beams

Both the flexural and shear strengths of RC beams can be substantially increased using externally bonded FRP reinforcement in the forms of sheets/strips/plates (all referred to as plates hereafter). Failures of such FRP-strengthened RC beams often occur by debonding of the FRP plate from the RC beam in a number of modes (Teng et al. 2002). Despite numerous theoretical and experimental studies, the current understanding of the mechanics of such debonding failures is still far from complete (Teng and Chen 2009). Because each of the different debonding failure modes is influenced by numerous factors, it is very cost- and time-intensive if not impossible to study the influence of each factor and their interactions in an exhaustive manner through laboratory tests. Therefore, accurate numerical modelling provides a very attractive and economical alternative research tool. Consequently, significant efforts have been expended by the authors' group in developing accurate finite element (FE) models for simulating the behaviour of FRP-strengthened RC structures.

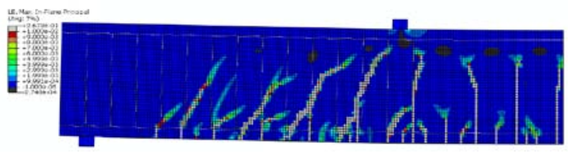
Our recent research has shown that, for accurate modelling of the full-range debonding behaviour of FRP-strengthened RC beams in various modes, it is essential to model all the following aspects in a rigorous manner:

a) flexural and shear cracking of concrete because debonding failure is closely related to concrete cracking;
b) bond-slip behaviour between FRP and concrete. Most of the debonding failure modes cannot even be predicted without the inclusion of an FRP-to-concrete bond-slip model;
c) bond-slip behaviour between steel reinforcements and concrete. The bond behaviour between steel and concrete can affect significantly the pattern and widths of cracks in the concrete which have an important effect on the accuracy of debonding prediction;
d) compressive behaviour of concrete and plasticity in steel reinforcements.

Significant recent advances have been made at PolyU in simulating intermediate crack induced debonding (IC debonding) in flexurally-strengthened RC beams (Chen et al. 2008, 2009b) and FRP debonding failure in shear-strengthened RC beams (Chen et al. 2009a). Figure 1 shows a comparison of the predicted IC debonding failure with the test results reported by Matthys (2000). Figure 2 compares the FE predictions with the test results of the shear-strengthened Specimen BS5 of Matthys (2000) which suffered FRP debonding failure.

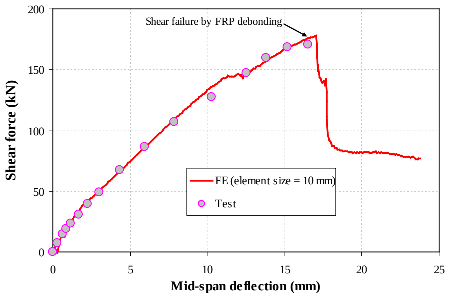


a) Load vs displacement



b) Predicted crack pattern at the ultimate state

Figure 1. Prediction of IC debonding failure: Specimen BF8 of Matthys (2000)



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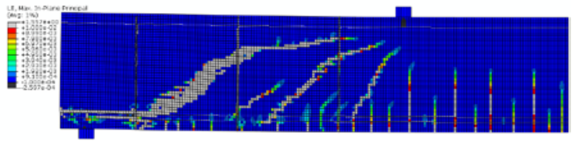


b) Predicted crack pattern at the ultimate state

Figure 2. Prediction of debonding failure in a shear-strengthened RC beam: Specimen BS5 of Matthys (2000)

FRP-jacketed RC slender columns

Provisions for the design of FRP jackets for strengthening RC columns have been included in a number of design guidelines (e.g. ACI 2008, Concrete Society 2004) based on the results of extensive research in the past two decades. A common deficiency in these design provisions is that the effect of column slenderness (i.e. second-order effect) has not been taken into account. A systematic study (Jiang 2008) on the modelling, behaviour and design of slender FRP-jacketed circular RC columns has recently been conducted at PolyU. Numerical results based on theoretical models developed in this study confirmed experimental observations that: 1) an RC column which is originally classified as a short column may need to be considered as a slender column after FRP jacketing; and 2) the effectiveness of FRP confinement decreases as the column slenderness increases. This is because the FRP confinement can substantially increase the axial load capacity of an RC section without significantly enhancing its flexural rigidity. A procedure for the design of FRP jackets to strengthen circular RC columns was then developed based on a comprehensive parametrical study. A set of equations for the design of slender columns, with the short column being a special case, was proposed. A slenderness limit for defining short FRP-confined circular RC columns was also developed.

FRP-confined high strength concrete

High strength concrete has been widely used in many structures but only a few studies have been concerned with the behavior and modeling of FRP-confined high strength concrete (Berthet *et al.* 2005; Mandal *et al.* 2005;

Almusallam 2006; Li 2006). Existing stress-strain models for FRP-confined concrete have been developed for normal strength concrete with the cylinder compressive strength below 50 MPa. The validity of these models for high strength concrete had not been verified. The behavior of FRP-confined high strength concrete with particular attention to the modeling of the behavior has recently been conducted at PolyU (Xiao et al. 2009). An experimental programme on FRP-confined concrete cylinders with the unconfined concrete strength varying from 71 MPa to 110 MPa was executed. No silica fume was used in these tests, but the effect of silica fume was given due attention. Xiao et al. (2009) concluded that the analysis-oriented model developed by Jiang and Teng (2007) for FRP-confined normal strength concrete also provides reasonably accurate predictions for FRP-confined high strength concrete without silica fume (Figure 3), although some discrepancies between the test results and the predicted stress-strain behavior do exist, especially when the FRP jacket has a low stiffness.

Silica fume is a common admixture for making high strength concrete. Existing test results from other studies have shown that silica fume has significant effects on the behavior of confined concrete, but how exactly silica fume affects this behavior is unclear (Xiao et al. 2009). Research is being conducted at PolyU to address this issue.

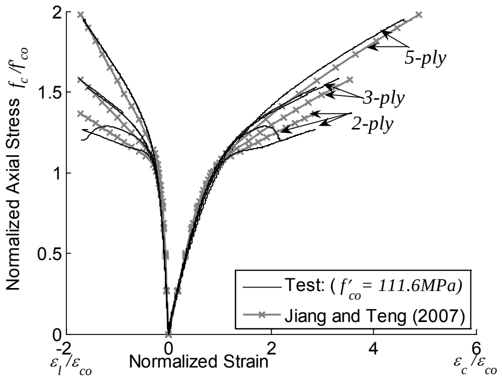
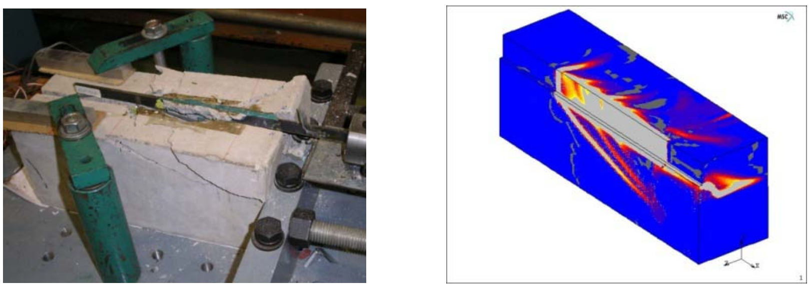


Figure 3 Test and predicted stress-strain curves of CFRP-confined high strength concrete

BEHAVIOR OF NEAR SURFACE-MOUNTED FRP IN CONCRETE

A promising alternative to externally-bonded FRP reinforcement for strengthening concrete structures is the near surface-mounted (NSM) FRP technique (e.g. Nanni et al. 1999, De Lorenzis and Nanni 2002, De Lorenzis and Teng 2007). A fundamental issue for this emerging technique is the bond behavior between a NSM FRP bar/strip and its surrounding concrete. Compared with an externally bonded FRP plate, an NSM FRP bar/strip exhibits much more complicated bond behavior with concrete as it depends on many more parameters such as the shape, surface configuration and size of the FRP reinforcement, the shape and size of the groove, and the tensile strengths of both the concrete substrate and the adhesive filler (generally an epoxy).

The bond behavior between NSM FRP and concrete has been one of the focuses of recent research at PolyU. A meso-scale three-dimensional FE model has been developed (Teng et al. 2009c) to predict the behavior of NSM FRP strips adhesively bonded to concrete using the general-purpose FE program MSC.MARC. The model is capable of accurate simulation of the initiation and propagation of interfacial debonding (Figure 4) in such joints observed in tests. The predicted load-displacement curve and strain distribution in the NSM FRP strip are also in close agreement with test results. From the results of this FE model, the local bond-slip curves for NSM FRP strips in concrete can be deduced (Figure 5).



a) Test b) Finite element prediction

Figure 4 Crack pattern of NSM FRP-to-concrete bonded joint

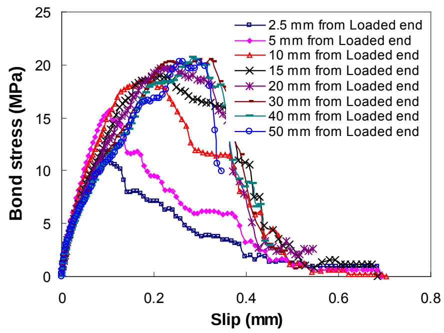


Figure 5 Local bond-slip curves of NSM FRP obtained from finite element analysis

PERFORMANCE-BASED SEISMIC RETROFIT OF RC STRUCTURES WITH FRP

The performance-based seismic design approach as presented in ATC-40 (1996), FEMA-356 (2000) and FEMA-440 (2005) is becoming widely accepted in structural engineering practice, particularly in the seismic assessment and retrofit of building structures. In this approach, the performance of a structure under seismic actions is commonly estimated by the performance point (e.g. ATC-40 1996) or the target displacement (e.g. FEMA-356 2000), and a push-over analysis of the structure is the essential key step. The popular open-source program "Open System for Earthquake Engineering Simulation" (OpenSees), developed at the University of California, Berkeley, offers a good programming platform for the numerical simulation of the seismic behavior of structures. OpenSees allows the introduction of new materials and elements as well as the updating of material constitutive models based on the latest research advances.

The seismic performance of a structure is controlled by its energy dissipation capacity under seismic actions. It has been widely shown that FRP jacketing of RC columns is a very effective means to enhance the seismic performance of existing seismically deficient RC structures. This is because FRP confinement can significantly improve the displacement ductility and hence the energy dissipation capacity of an RC column. Two recent publications have been concerned with the seismic analysis of concrete-filled FRP tubes (Zhu *et.al*. 2006) and FRP- wrapped RC columns (Mosalam *et.al*. 2007) respectively using OpenSees, but there is a lack of a robust material model for FRP-confined concrete under cyclic loading.

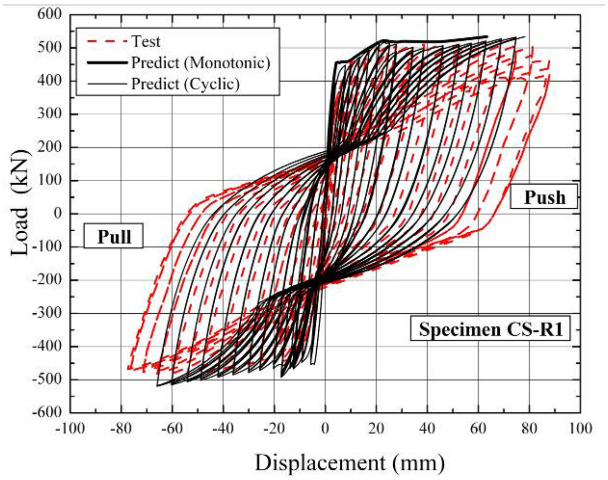
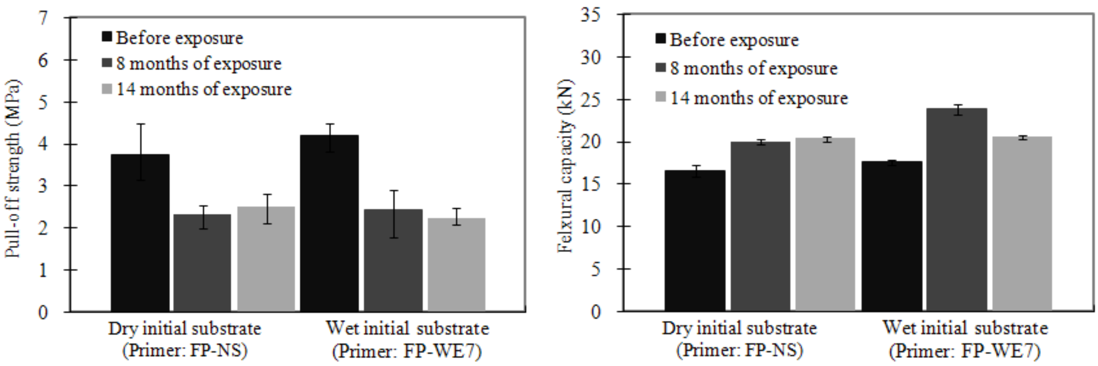


Figure 6 Hysteretic behaviour of an FRP-jacketed RC column

A major research project on the seismic retrofit of RC structures with FRP is currently under way at PolyU, motivated by the expectation that many of the concrete buildings in Hong Kong designed without consideration of seismic risks will need to be seismically retrofitted in the foreseeable future. The first stage of the project has been the implementation of the latest knowledge developed at PolyU on FRP-confined concrete into OpenSees to support the performance-based seismic design of FRP-retrofitted RC columns/structures (Lu et al. 2009). In this work, a cyclic stress-strain model for FRP-confined concrete proposed by Lam and Teng (2009), with the envelope curve described by Teng et al.'s (2009a) model, which is an improved version of Lam and Teng's (2003) design-oriented model, was implemented in OpenSees as dynamic library link (DLL) files. This model can predict the stress-strain responses of concrete subjected to monotonic and cyclic compression in pushover, cyclic or time history response analyses. In addition, Yassin's (1994) model for the hysteretic behavior of concrete in tension available in OpenSees was modified to represent the effect of compressive deterioration on the tensile stiffness of concrete in a more reasonable manner. An existing constitutive model for steel in OpenSees was used to simulate the behavior of the longitudinal steel reinforcement. Figure 6 shows a comparison between the test response of an FRP-jacketed RC column subjected to a constant axial load and cyclic lateral forces and the initial results of pushover (monotonic) analysis and cyclic analysis using OpenSees with the newly implemented stress-strain model for FRP-confined concrete. In these analyses, the bond-slip behavior of longitudinal steel bars was not considered. The analyses were terminated when the ultimate axial strain of FRP-confined concrete predicted from the material ultimate tensile strain of the FRP obtainable from coupon tests was first reached by the extreme compression fiber of the column. More detailed information on the simulation procedure and the simulation results is given in Teng et al. (2009b).

DURABILITY OF FRP-TO-CONCRETE BONDLINES

The bond behavior between FRP and concrete often controls the failure of an FRP-strengthened RC structure. This is particularly true for flexurally- and shear-strengthened RC beams. In order to establish a safe and economical approach for the durability design of FRP-strengthened RC structures, a good understanding of the durability of the FRP-to-concrete bondline (including the adhesive layer) is necessary. Research has recently been conducted on the effect of combined moisture and thermal cycling on the long-term behavior of the FRP-to-concrete bondline in terms of its tensile and shear performance using pull-off tests of FRP plates bonded to plain concrete cubes and bending tests of plain concrete beams strengthened with a soffit FRP plate (Dai and Yokota, 2009). It has been found that, after exposure to an environment of accelerated dry/wet cycles, all FRP-to-concrete bonded joints failed at the interface between the primer and concrete, instead of within the concrete substrate as observed in un-exposed specimens. The tensile bond strength from the pull-off test was reduced by about 50% after 8 months of exposure, but no further reduction was observed when the exposure period was increased to 14 months (Figure 7a). However, the loss of tensile bond strength did not necessarily lead to the same loss of the shear transfer capacity of the bondline in the bending test. The flexural capacity of the FRP-strengthened RC beams after exposure was even higher than those without exposure (Figure 7b) as a softer bondline increases the effective bond length (Chen and Teng 2001). Data after exposure for two years will become available soon. This research aims to develop a theoretical model to predict the behavior of FRP-to-concrete bondlines after environmental exposure involving moisture and thermal cycling.



(a) Tensile pull–off test (b) Bending test

Figure 7 Performance of FRP-to-concrete interfaces after combined wet/dry and thermal cycling

HYBRID STRUCTURES INCORPORATING FRP

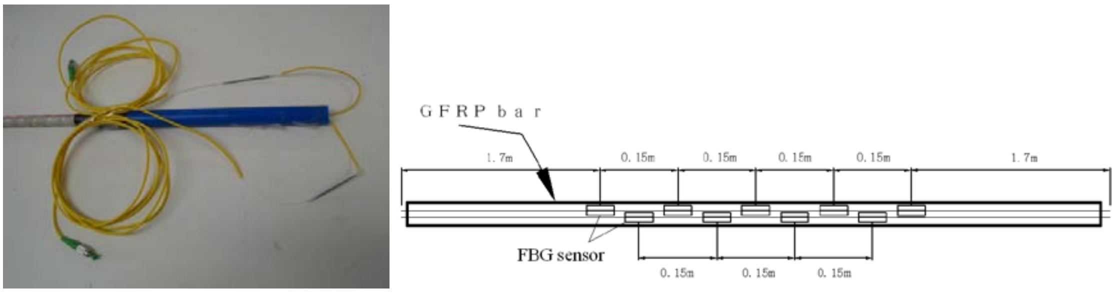
FRP composites have been applied in new construction in various forms. Examples of such applications include concrete-filled FRP tubes (CFFTs) (Mirmiran and Shahawy 1996), FRP-confined concrete-filled steel tubes (CFSTs) (Xiao 2004; Xiao et al. 2005) and hybrid FRP-concrete-steel double-skin tubular columns (DSTCs) (Teng et al. 2007). They make use of the beneficial effects of FRP confinement to concrete and offer a number of advantages over traditional RC columns. A great deal of recent research has been conducted on these three types of hybrid FRP-concrete columns at PolyU.

A recent study at PolyU on the behavior of CFFTs has led to the development of a design proposal for this type of hybrid FRP-concrete structures (Yu and Teng 2009). The design proposal addresses the unique properties of the FRP tube and those of the confined concrete and has been adopted by the draft Chinese Code for Infrastructure Applications of FRP Composites. Within a comprehensive ongoing research programme on FRP-confined CFSTs, three series of monotonic axial compression tests, two series of cyclic axial compression tests as well as a series of large column tests were conducted; in the last series of tests, the columns were subjected to a constant axial load in combination with either a monotonic or a cyclic lateral load. These tests have confirmed that the presence of the FRP jacket enhances both the load carrying capacity and the ductility of the column (Hu et al. 2009).

The hybrid DSTC column, invented by the first author of this paper, consists of an FRP outer tube, a steel inner tube and an annular concrete infill between these two tubes. The three constituent materials can be very efficiently used in this column to produce the desired strength and stiffness. Hybrid DSTCs with normal strength concrete have a ductile response under monotonic axial compression (Yu et al. 2006; Wong et al. 2008). More recent tests conducted at PolyU have also confirmed that hybrid DSTCs, with proper design, can still be very ductile under axial compression even when high strength concrete is used. The cyclic behavior of hybrid DSTCs is being studied. This hybrid DSTC column form offers great potential for wide application in many different structures (e.g. bridge piers and towers) due to its many advantages over hollow RC columns including excellent ductility and corrosion resistance as well as ease for construction (no temporary forms and steel re-bars are needed).

SMART FRP-REINFORCED CONCRETE STRUTURES

FRP rebars have been used as internal reinforcement in concrete structures to replace traditional steel reinforcement. This is particularly beneficial for structures in highly corrosive environments such as marine environments where steel rebars are vulnerable to corrosion. Although it is expected that FRP-reinforced concrete structures is highly resistant to environmental attacks, there is still significant uncertainty in their true long-term performance due to the lack of long-term service data of such structures. Long-term structural health monitoring of such structures is therefore important.



(a) Smart GFRP bar (b) FBG sensors in the smart GFRP bar

Figure 8 A smart GFRP bar

Figure 9 Bending test of a concrete beam reinforced with smart GFRP bars

At PolyU, smart FRP rebars incorporating fiber-optic sensors have been successfully developed (Wang et al. 2009). Such rebars combine the functions of structural reinforcement and long-term field monitoring. Figure 8a shows a sample smart GFRP bar. Two optical fibers with 9 fibre Bragg grating (FBG) sensors in total were embedded at the centre of this 13 mm diameter bar during the pultrusion process (Figure 8b). A 150× 250× 2700 mm concrete beam reinforced with two such smart GFRP tension rebars were built for a pilot test. This beam also contained two compression GFRP rebars each with a single FBG sensor for the monitoring of compression strains. This beam was loaded in four-point bending to failure to demonstrate its structural performance and sensing capability (Figure 9). The FBG sensors worked very well during the test. The strain readings obtained from the FBG sensors were in excellent agreement with those obtained from strain gauges bonded on the surface of the rebars, demonstrating the excellent performance of smart GFRP rebars.

CONCLUSIONS

This paper has presented a summary of some of the recent and current research at The Hong Kong Polytechnic University on the structural use of FRP composites in civil engineering. Apart from the topics covered here, the PolyU group is also working on a number of other topics, including the strengthening of metallic structures, the strengthening of RC beam-column joints, and the development of a design guideline for strengthening RC structures for Hong Kong. The central theme of the group's research is to develop an in-depth understanding of the fundamental mechanics of structures incorporating FRP and to develop rational theoretical models for their analysis and design.

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