Performance enhancement of bridges and other structures through the use of fibre-reinforced polymer (FRP) composites: some recent Hong Kong research

J G. Teng  
*Hong Kong Polytechnic University, cejgteng@polyu.edu.hk*

S S. Zhang  
*Hong Kong Polytechnic University, shishun@uow.edu.au*

Q G. Xiao  
*Hong Kong Polytechnic University*

D Fernando  
*University of Queensland, dilum.fernando@uq.edu.au*

B Zhang  
*Hong Kong Polytechnic University*

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Abstract
Due to their various advantages including excellent corrosion resistance and high strength-to-weight ratios, fibre-reinforced polymer (FRP) composites have been widely used as strengthening materials to enhance the performance of existing structures including bridges. In addition, FRP composites have attracted increasing attention for use in the construction of high-performance bridges and other structures. This paper presents a summary of some recent research undertaken at The Hong Kong Polytechnic University (PolyU) in both areas. The paper covers the following topics of significant current interest examined in four recent PhD projects under the supervision of the first author: (1) strengthening of reinforced concrete (RC) beams with near-surface mounted (NSM) carbon FRP (CFRP) strips; (1) strengthening of steel members with externally-bonded (EB) CFRP plates/sheets; (2) computational models for FRP-confined RC columns; and (4) hybrid FRP-concrete steel double-skin tubular columns (DSTCs) for high-performance bridges/structures. These studies have led to significant advances in understanding and predicting the behaviour of structures whose performance has been augmented through the use of FRP composites.

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Performance Enhancement of Bridges and Other Structures through the Use of Fibre-Reinforced Polymer (FRP) Composites: Some Recent Hong Kong Research

J.G. Teng 1,*, S.S. Zhang 1, Q.G. Xiao 1, D. Fernando 2 and B. Zhang 1
1Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, China.
2School of Civil Engineering, The University of Queensland, QLD 4072, Australia
*cejgteng@polyu.edu.hk

ABSTRACT: Due to their various advantages including excellent corrosion resistance and high strength-to-weight ratios, fibre-reinforced polymer (FRP) composites have been widely used as strengthening materials to enhance the performance of existing structures including bridges. In addition, FRP composites have attracted increasing attention for use in the construction of high-performance bridges and other structures. This paper presents a summary of some recent research undertaken at The Hong Kong Polytechnic University (PolyU) in both areas. The paper covers the following topics of significant current interest examined in four recent PhD projects under the supervision of the first author: (1) strengthening of reinforced concrete (RC) beams with near-surface mounted (NSM) carbon FRP (CFRP) strips; (2) strengthening of steel members with externally-bonded (EB) CFRP plates/sheets; (3) computational models for FRP-confined RC columns; and (4) hybrid FRP-concrete-steel double-skin tubular columns (DSTCs) for high-performance bridges/structures. These studies have led to significant advances in understanding and predicting the behaviour of structures whose performance has been augmented through the use of FRP composites.

KEY WORDS: FRP composites, strengthening, debonding, confinement, new construction

1 INTRODUCTION

The use of fibre-reinforced polymer (FRP) composites for the strengthening and construction of bridges and other structures has emerged as an important civil engineering research area over the past two decades (e.g. Teng et al. 2002; Bank 2006; Balaguru et al. 2008; Hollaway and Teng 2008; Zhao 2014). This emergence has largely been due to the superior properties of FRP composites including their excellent corrosion resistance and high strength-to-weight ratios. As a new class of strengthening materials, FRP composites offer a cost-effective solution to extend the service life of structures including bridges. In new construction, FRP composites can be used to reinforce concrete (RC) to eliminate the steel corrosion problem, leading to more durable structures.

In the strengthening of bridges to address safety issues related to either deterioration or increased traffic loading, bonded FRP reinforcement has become a mainstream technology. For concrete structures, strengthening using externally bonded (EB) FRP reinforcement has received extensive research attention (e.g. Teng et al. 2002; Hollaway and Teng 2008), and reasonably robust design guidelines have been established. In more recent years, the strengthening of concrete structures using near-surface mounted (NSM) FRP reinforcement (De Lorenzis and Teng 2007) and the strengthening of steel structures using EB FRP reinforcement (Teng et al. 2012) have received increasing attention. These two topics will be first addressed in the present paper.

Both FRP and concrete are non-ductile, but when concrete is confined with FRP, the FRP-confined concrete so obtained can exhibit a highly ductile response. This phenomenon has been exploited in both the strengthening of RC columns (i.e. FRP jacketing of RC columns) and the construction of new columns (i.e. concrete-filled FRP tubes). As a result, it is very important to develop a good understanding of the behaviour of FRP-confined concrete in various sectional shapes and to be able to predict this behaviour. This issue forms the third topic of the present paper.

In the construction of new structures including bridges, the use of FRP composites has been explored in many different ways. Examples include the use of FRP reinforcing bars to replace steel bars in concrete structures and the use of FRP cables to replace steel cables. The authors believe that one of the most promising applications for FRP composites in new structures/bridges should come from a combined use of FRP with steel and concrete to create what are called “hybrid FRP-concrete-steel members”. The first author proposed a new form of hybrid columns in 2004 (Teng et al. 2004) and has been working on this form of columns over the past 10 years. The latest research on this form of hybrid columns is presented as the final topic of this paper.
The studies summarised in this paper have been undertaken as four recent PhD research projects by the four co-authors of the paper under the supervision of the first author. These studies have led to significant advances in understanding and predicting the behaviour of structures whose performance has been augmented through the use of FRP composites.

2 STRENGTHENING OF RC BEAMS WITH NSM CFRP STRIPS

2.1 Introduction

The method of strengthening RC structures using NSM FRP reinforcement has attracted increasing attention in recent years as a promising alternative to EB FRP reinforcement (e.g. De Lorenzis and Teng 2007). In the NSM FRP method, grooves are cut into the concrete cover of RC members for the embedding of FRP bars using an adhesive. The study recently completed at PolyU (Zhang 2012) was focussed on the flexural strengthening of RC beams with NSM CFRP strips. In NSM FRP strengthening, CFRP is preferable to other FRPs as the higher strength and elastic modulus of CFRP leads to a smaller cross-section for the same tensile force or stiffness, so CFRP bars can be more easily accommodated within the concrete cover; in addition, in terms of cross-sectional form, strips (with a narrow rectangular section) are preferable to other forms of bars as strips have a larger perimeter for bonding for the same cross-sectional area.

Existing laboratory tests on RC beams strengthened in flexure with NSM CFRP strips have identified several debonding failure modes (Zhang 2012). Out of these debonding failure modes, end cover separation, which involves the detachment of the NSM FRP reinforcement together with the concrete cover along the level of the steel tension reinforcement (Figure 1), has been observed most frequently in tests and is the main debonding failure mode of concern in PolyU’s study (Zhang 2012). A brief summary of this study is presented below.

2.2 Behaviour of NSM CFRP-to-Concrete Bonded Joints

2.2.1 Meso-Scale FE Modelling of Bonded Joints

A 3-D meso-scale finite element (FE) approach was developed using the general-purpose FE software package MSC.MARC (MSC.MARC 2005) for the bond behaviour of NSM CFRP strips in concrete (Teng et al. 2013). The concrete was simulated using the orthogonal fixed smeared crack model while the FRP and the adhesive were treated as linear-brittle materials. The well-documented tests of Li et al. (2005) were used to calibrate and verify the proposed FE approach. The predicted failure mode is shown in Figure 2. The FE predictions (e.g. load-displacement curve and failure mode) are in close agreement with the test results. Most importantly, local bond-slip curves were extracted from the FE predictions of the axial strains in the CFRP strip. For more details of the study, the reader is referred to Teng et al. (2013).

Figure 2. Predicted failure mode of NSM CFRP strip-to-concrete bonded joint (half-specimen model)

![Figure 2. Predicted failure mode of NSM CFRP strip-to-concrete bonded joint (half-specimen model)](image)

Figure 3. Bond-slip curves for NSM CFRP-to-concrete interfaces with a concrete cylinder compressive strength of 30 MPa

![Figure 3. Bond-slip curves for NSM CFRP-to-concrete interfaces with a concrete cylinder compressive strength of 30 MPa](image)
2.2.2 Bond-Slip Model for NSM CFRP Strips in Concrete

By making use of the 3-D meso-scale FE model (Teng et al. 2013) introduced in the preceding sub-section, a parametric study was conducted to generate numerical data for bond-slip responses. Based on these numerical results, the following bond-slip model, including expressions for the interfacial fracture energy \( G_f \) and the maximum bond shear stress \( (\tau_{\text{max}}) \), was formulated (Zhang et al. 2013a):

\[
\tau = A \left( \frac{2b-s}{B} \right)^2 \sin \left( \frac{\pi}{2} \frac{2b-s}{B} \right) \quad \text{with} \quad s \leq 2B
\]

\( (1) \)

\[
G_f = 0.4 \gamma^{0.422} f_c^{0.619}
\]

\( (2) \)

\[
\tau_{\text{max}} = 1.15 \gamma^{0.138} f_c^{0.613}
\]

\( (3) \)

where \( \tau \) and \( s \) are the bond shear stress and the shear slip respectively; \( A = 0.72 \gamma^{0.138} f_c^{0.613} \) and \( B = 0.37 \gamma^{0.284} f_c^{0.006} \); and \( \gamma \) is the groove height-to-width ratio \( (h/s) \). Comparisons of the bond-slip curves for three selected cases between the FE results and the proposed model are shown in Figure 3, showing close agreement. For more details, the reader is referred to Zhang et al. (2013a).

2.2.3 Bond Strength Model of NSM CFRP Strips in Concrete

The basic equation for the bond strength is (see Yuan et al. 2004)

\[
P_b = \sqrt{2G_f E_f A_f C_{\text{failure}}} \quad \text{when} \quad L_b \geq L_c
\]

\( (4) \)

\[
P_b = \beta L \sqrt{2G_f E_f A_f C_{\text{failure}}} \quad \text{when} \quad L_b < L_c
\]

\( (5) \)

where \( G_f \) is the interfacial fracture energy (Equation 2); \( L_b \) is the bond length; \( L_c \) is the effective bond length; \( E_f \) and \( A_f \) are the elastic modulus and the cross-sectional area of the CFRP strip respectively; \( C_{\text{failure}} \) is the cross-sectional contour of the failure surface which is here taken to be composed of the three sides of the groove surrounding the adhesive layer; and \( \beta \) is a reduction factor to account for the effect of insufficient bond lengths. Based on numerical results from a simple beam-spring numerical model (Zhang et al. 2013b), the following equations were proposed for the effective bond length \( L_c \) and the reduction factor \( \beta_L \):

\[
L_c = \frac{1.66}{\eta} \quad \text{where} \quad \eta^2 = \frac{\tau_{\text{max}}^2 C_{\text{failure}}}{2G_f E_f A_f}
\]

\( (6) \)

\[
\beta_L = \frac{L_b}{L_c} (2.08 - 1.08 \frac{L_b}{L_c})
\]

\( (7) \)

A comparison between the bond strengths predicted by the proposed model (i.e. Equations 4 to 7) and those predicted by the only existing bond strength model for such bonded joints (Seracino et al. 2007) with the results of 51 test specimens collected from 7 existing studies showed that the proposed model performs significantly better than Seracino et al.’s (2007) model. For more details of the comparison, the reader is referred to Zhang et al. (2013b).

2.3 Strength Model for End Cover Separation in RC Beams Strengthened with NSM CFRP Strips

2.3.1 2-D Nonlinear FE Approach for End Cover Separation

In the proposed 2-D nonlinear FE approach for RC beams strengthened in flexure with NSM FRP reinforcement, the bond-slip relationship between steel bars and concrete and that between FRP and concrete were accurately modelled; and the critical debonding plane along the level of the tension steel bars was given special attention. The modelling of concrete and FRP is similar to that in the meso-scale modelling of NSM CFRP strip-to-concrete bonded joints as explained above, and the steel reinforcement was modelled as an elastic-perfectly plastic material. Most importantly, a special cohesive-element-pair (CEP) (Figure 4) was proposed to represent the effect of radial stresses generated by the steel tension bar (Zhang and Teng 2010). Comparisons between predictions and test results, for the ultimate shear forces of the 45 collected specimens at failure, suggested for the first time ever that these radial stresses play an important role in cover separation failure and need to be taken into account to achieve accurate FE predictions.

![Figure 4. Cohesive-element-pair (CEP)](image)

2.3.2 Simplified FE Approach for End Cover Separation

If the strain in the FRP at the inside crack adjacent to the plate end (Point A in Figure 5) at end cover separation is known, the moment acting on the corresponding section can be easily found through section analysis if the plane section assumption is still adopted; the ultimate load can then be easily calculated. Therefore, the part of the RC beam between the two cracks near the FRP bar end can be isolated to form a simple model for FE analysis to obtain the failure strain in the FRP at the inside cracked section (Point A in Figure 5) (Zhang and Teng 2013). A comparison of the failure shear forces between the predictions of the simplified FE approach (a section analysis is necessary) and five test results for which the crack spacing of concern could be measured directly from pictures of crack patterns verified the performance of the proposed simplified FE approach (Zhang and Teng 2013).
2.3.3 Analytical Strength Model for End Cover Separation

To predict the ultimate shear force of an FRP-strengthened RC beam at end cover separation, the failure strain in the FRP at the inside cracked section (Point A in Figure 5) and the position of this cracked section both need to be known. The crack spacing determines both the failure strain in the FRP at the inside cracked section and the position of this cracked section (i.e. distance from the nearest support). In the present work, the crack spacing model proposed by Zhang et al. (1995) was adopted. Based on a regression analysis of results of a parametric study conducted using the proposed simplified FE approach, an expression for the FRP strain at the inside cracked section at concrete cover separation failure was established (Zhang et al. 2012a). This new strength model offers significantly closer predictions of the available test results than the existing models. More evidence for the superior performance of the proposed debonding strain model can be found in Zhang et al. (2012a).

3 STRENGTHENING OF STEEL MEMBERS WITH CFRP

3.1 Introduction

While extensive research has been conducted on the strengthening of concrete and masonry structures with EB FRP reinforcement, the potential of EB FRP reinforcement in strengthening steel structures has been explored only to a limited extent (Teng et al. 2012; Zhao 2013); therefore many aspects are yet to be properly investigated, particularly the behaviour of CFRP-to-steel bonded interfaces. A good understanding of CFRP-to-steel interfacial behaviour provides the key for designing against various debonding failure modes (Figure 6), which is a critical issue in strengthening steel structures with CFRP. Against this background, the author’s group recently completed a study on the bond-behaviour and debonding failure of CFRP-to-steel interfaces. The outcomes of the study (Fernando 2010) are briefly summarised below.

3.2 Steel Surface Preparation

A systematic experimental study (Fernando et al. 2013) was carried out to examine the effects of steel surface preparation methods and adhesive properties on the adhesion strength between steel and adhesive, and to explore the possibility of avoiding adhesion failure (Figure 6) through appropriate treatment of the steel surface. Two types of tests were used: tensile butt-joint tests and single-lap shear tests.

The test results showed that the grit-blasting method results in significantly higher adhesion strengths than the other investigated methods (i.e. solvent-cleaning and hand-grinding after solvent-cleaning). For all the five types of adhesives studied, both the tensile butt-joint tests and the shear-lap shear tests revealed that it is possible to avoid pure adhesion failure by providing appropriate treatment to the steel surface. This experimental study also suggested that, for adhesive bonding, the steel surface should be solvent-cleaned, grit-blasted using angular grit, and then further cleaned using a vacuum head. The study further showed that the measured surface characteristics (i.e., surface energy, surface chemical composition, and surface roughness and topography) are consistent after being grit-blasted using the same grit, which suggests the possibility of developing a standard preparation process to achieve a steel surface with a sufficient adhesion strength.
bonded joints (Teng et al. 2002), there exists an effective bond length in such bonded joints, beyond which any further increase in the bond length does not lead to a further increase in the bond strength but does lead to an increase in the ductility of the failure process. The bond strength was found to increase with both the adhesive thickness and the FRP plate axial rigidity, provided that cohesion failure is the controlling failure mode.

3.3.2 Bond-Slip Models

Based on experimental observations, two bond-slip models were proposed for linear adhesives (Fernando 2010). The two bond-slip models (the shape of the simpler model, a bi-linear model, is shown in Figure 7a) were revised from similar models proposed by Lu et al. (2005) for FRP-to-concrete bonded joints, but taking due account of the unique characteristics of CFRP-to-steel bonded interfaces. The two bond-slip models both compare well with the test results. For CFRP-to-steel bonded interfaces with a non-linear adhesive, a preliminary trapezoidal bond-slip model was proposed, which is composed of a linear ascending branch, a constant stress branch and a linear descending branch (Figure 7b). While the trapezoidal model needs to be further developed/verified when additional test data become available, it is believed that the trapezoidal shape captures well the bond-slip characteristics of such bonded interfaces.

3.3.3 Analytical Solution for CFRP-to-Steel Bonded Joints

Based on a trapezoidal bond-slip model (with a triangular model as a special case), an analytical solution (Fernando et al. 2014) was developed for predicting the full-range behaviour of CFRP-to-steel bonded joints with a non-linear adhesive, following the approach of Yuan et al. (2004). The analytical solution provides closed-form expressions for the interfacial shear stress distribution and the load-displacement behaviour at different loading stages. The analytical solution was found to represent the test results closely. As part of the analytical solution, a bond strength model was also derived, including an expression for the effective bond length. As expected, the bond strength model provides accurate predictions for bonded joints with either a linear adhesive or a non-linear adhesive.

3.4 FE Modelling of Debonding Failures

3.4.1 CFRP-to-Steel Interfaces under Mixed-Mode Loading

By making use of the bond-slip model for linear adhesives developed in the present work, a coupled cohesive zone model was proposed for modelling the CFRP-to-steel interface subjected simultaneously to mode I and mode II loading (mixed-mode loading) (Fernando 2010). This cohesive zone model employs a mixed-mode cohesive law considering the effect of interaction between mode I loading and mode II loading on damage propagation within the adhesive layer. Damage initiation was defined using a quadratic strength criterion, and damage evolution was defined using a linear fracture energy-based criterion, both of which account for the effect of mixed-mode loading. The proposed approach represents a significant advancement in the modelling of debonding failures in CFRP-strengthened steel structures.

3.4.2 Debonding Failures in Steel Beams

*Strengthened in Flexure with a Bonded CFRP Plate*

Before the PolyU work (Fernando 2010), no theoretical model had been developed that is capable of accurate predictions of debonding failures in CFRP-strengthened steel beams. An FE approach was therefore developed at PolyU (Fernando 2010) to correct this deficiency of existing knowledge, using the coupled cohesive zone model discussed above for CFRP-to-steel interfaces. Predictions from this FE approach were found to compare well with the test results (Figure 8) reported by Deng and Lee (2007) for those CFRP-strengthened steel beams failing by either end debonding or compression flange buckling. Using the proposed FE approach,
the behaviour of CFRP-strengthened steel beams was further examined.

3.4.3 Debonding Failures in CFRP-Strengthened RHS Tubes Subjected to an End Bearing Load

This problem of local CFRP strengthening of rectangular steel tubes under an end bearing load was first studied by Zhao et al. (2006). The PolyU study (Fernando 2010) included a series of tests on the effects of adhesive types and web slenderness as well as an FE study (Fernando et al. 2012) employing the coupled cohesive zone model described in the preceding sub-section. The FE approach was shown to closely predict the experimental behaviour of these CFRP-strengthened tubes. The FE results also showed that debonding in such tubes is governed by interfacial normal stresses. Assuming a perfect bond between CFRP and steel, an initial design model was proposed to predict the load-carrying capacity of CFRP-strengthened RHS tubes. To account for the effect of debonding, two reduction factors were next introduced and these factors depend on the adhesive mechanical properties and the web slenderness.

4 FE MODELLING OF FRP-CONFINED RC COLUMNS

4.1 Introduction

Confinement can significantly enhance the strength and the deformation capacity of concrete (Teng and Lam 2004). The confinement provided by FRP to concrete is passive in nature, and the confinement mechanism can become rather complex if the column section is non-circular (Yu et al. 2010b). The behaviour of uniformly-confined concrete (as found in FRP-jacketed circular plain concrete columns) is now well understood and can be closely predicted (e.g. Jiang and Teng), but the same is not true about concrete under non-uniform confinement (e.g. concrete confined by discrete steel hoops and FRP-confined rectangular concrete columns). For concrete under non-uniform confinement, the FE method offers a highly promising approach for understanding and predicting its behaviour. The key to successful FE modelling of concrete under non-uniform confinement is an accurate constitutive model for concrete under trial-axial compression. The author’s group has recently completed a new study (Xiao 2013) on the identification/development of accurate concrete constitutive models for use in the FE modelling of non-uniformly confined concrete on basis of a previous study on the same topic (Yu et al. 2010a, 2010b) which established an accurate plastic-damage model for concrete for use in modelling confined concrete. In the new study (Xiao 2013), the attention was focussed on an alternative constitutive model for concrete [namely the microplane model formulated by Bazant et al. 2000] and the development of a 3D model for FRP-confined RC columns. The outcomes of this new study are summarised below.

4.2 Microplane Model for Confined Concrete

In recent years, the micro-plane model (Bazant et al. 2000) has attracted increasing attention from researchers interested in modelling the stress-strain behaviour of confined concrete (e.g. Liu and Foster 2000). This approach relies on stress-strain relationships at the microscopic level instead of those at the macroscopic level; it is based on the concept of microplanes which may be imagined as damage/weak planes in the micro-structure of concrete. It is widely known that certain macroscopic phenomena of concrete can be interpreted using microscopic mechanisms. Therefore, it was suspected that the microplane model as a constitutive model could well have a better capability than macroscopically-based constitutive models for modelling the behaviour of confined concrete. In the recent study undertaken at PolyU (Xiao 2013), the fourth version of the microplane model (M4) was used. Later versions of the micro-plane model (M4) are available, but the improvements included in the later versions are unimportant to the modelling of static behaviour of
Some drawbacks had previously been found in the original M4 model (Tue et al. 2008), including: directional bias for micro shear stresses, strain increment magnitude dependence, integration scheme dependence and significant loading direction dependence (Tue et al. 2008). These drawbacks were eliminated in the present numerical implementation [as a user subroutine for ABAQUS (2004)] by adopting the algorithm proposed by Nemecek et al. (2002) and Tue et al. (2008). In addition, the M4 model was further modified to better predict the behaviour of confined concrete. These modifications led to the so-called M4+ model (Xiao 2013). Three parameters of the M4+ model were made confinement-dependent. The results of the M4+ model were compared with test results of FRP-confined square columns. Figure 9 shows that the stress-strain curves predicted by the M4+ model are in close agreement with the corresponding test results of FRP-confined concrete in square columns.

![Figure 9](image1.png)

Figure 9. Comparison between FE and test results for an FRP-confined RC column tested by Eid et al. (2009)

### 3.3 3D FE Modelling of FRP-Confined RC Columns

Although some attempts have been made at developing 3D models of RC columns or FRP-confined RC columns with non-uniform confinement over the height due to the presence of steel hoops, no accurate FE model of this type had previously been developed. In Xiao (2013), an accurate FE approach was developed to predict 3D behaviour of FRP-confined RC columns based on the plastic-damage model for concrete developed by Yu et al. (2010b). The plastic-damage model proposed by Yu et al. (2010b) was previously used with success in a slice model containing a single layer of elements in modelling FRP-confined concrete columns where the confinement is uniform throughout the column height. This slice model was also used in modelling FRP-confined square columns with success. The FE results based on this model were shown to be also in close agreement with the corresponding test results. was used in this 3D column model. The plastic-damage model was deemed to be similar in accuracy and simpler in nature than the M4+ microplane model developed in the same study (Xiao 2013).

In the proposed 3D FE approach (Xiao 2013), non-uniform confinement/deformation over the height of the column, due to features such as end restraints and discrete steel hoops, can be properly represented. This FE approach was shown to be successful in predicting the behaviour of large-scale RC columns (Figure 10).

#### 5 HYBRID DSTCS WITH NSC AND HSC

Hybrid FRP-concrete-steel double-skin tubular columns (hybrid DSTCs) are a novel form of structural members developed at PolyU (Teng et al. 2004, 2007). A hybrid DSTC consists of an outer tube made of FRP and an inner tube made of steel, with the space between filled with concrete (Figure 11). The outer FRP tube has fibers oriented close to the hoop detection to confine the concrete and enhances the shear resistance of the member. The two tubes serve as the stay-in-place form during construction. In hybrid DSTCs, the three constituent materials are combined in an optimal manner to achieve several advantages not available with existing columns, including their excellent corrosion resistance, ductility and seismic resistance. Hybrid DSTCs are highly attractive for use as bridge columns. Since the invention of hybrid DSTCs, a large amount of research has been conducted on this member form (Zhang 2014). However, most of the previous research on hybrid DSTCs was limited to monotonic loading and the testing of small normal strength concrete (NSC) columns (e.g. Yu et al. 2010b). The latest study on DSTCs at PolyU (Zhang 2014) was focused on seismic behaviour and the use of high-strength concrete (HSC).

![Figure 11](image2.png)

Figure 11. Cross-section of hybrid DSTCs

As part of the latest experimental study on DSTCs, eight large-scale circular hybrid DSTCs with a diameter of 300 mm and a height of 1350 mm were tested under cyclic lateral loading in combination with constant axial compression (Zhang et al. 2012b). The concrete strength of these specimens ranged from 37.4 MPa to 117.3 MPa; the
thickneses of the GFRP tube were 6mm or 10mm with the fibres being ±80 degrees to the longitudinal axis of the tube; two axial load ratios (i.e. 0.2 and 0.4) were adopted in these tests. Figure 12 shows aspects of a DSTC after a cyclic lateral loading test. Figure 13 shows the experimental hysteresis loops from the cyclic lateral loading test of a DSTC filled with HSC. Despite the use of HSC, the DSTC displayed highly ductile behaviour and an excellent energy absorption capacity.

Figure 12. Hybrid DSTC after test

![Global view](image1)

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<tr>
<th>Global view</th>
<th>Damage to the GFRP tube</th>
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<td><img src="image3" alt="Damage to the GFRP tube" /></td>
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<th>Damage to the concrete</th>
<th>Damage to the steel tube</th>
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<td><img src="image4" alt="Damage to the concrete" /></td>
<td><img src="image5" alt="Damage to the steel tube" /></td>
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Figure 13. Hysteresis loops of a DSTC filled with HSC

\[ f_{co} = 116.4 \text{ Mpa}; \ 6.0 \text{mm GFRP tube}; \ n = 0.2 \]

6. CONCLUSIONS

This paper has summarized four recent studies undertaken at PolyU by the author’s group on the structural use of FRP composites to enhance the performance of structures including bridges. The NSM FRP strengthening method is an attractive alternative to the EB FRP strengthening method in bridge strengthening, but its wider use requires more research and the development of design guidance documents. The strengthening of steel and steel-concrete bridges/structures is an important topic, so FRP strengthening can be expected to play a more prominent role in the future as more research and sound design rules become available. The use of FRP in new bridge construction, based on optimal combinations of FRP, concrete and steel, is highly promising. One of the most beneficial ways of combining FRP and concrete is to confine concrete with FRP so that ductile structural responses are obtained from the combination of two non-ductile materials. Much more research is still needed on ways of combining these materials, and on the behaviour and design of hybrid structures based on the combined use of these materials.

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