FRP in China: the state of FRP research, design guidelines and application in construction

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ABSTRACT: This paper presents the state of FRP research and design guidelines in construction in the mainland of China. It covers structural strengthening with FRP sheets and plates, reinforced concrete structures with FRP bars and tendons, all FRP structures and bridges, and FRP-concrete composite structures.

1 INTRODUCTION

Research on FRP in construction in the mainland of China may be traced back to the end of 1950s when China was in short supply of steel. The purpose of the research was to explore the use of GFRP bars instead of steel bars in RC T-section beams. But the beam failed in a very brittle manner with a sudden rupture of the GFRP bars, and the research was not continued. In 1982, a highway bridge of 20.7m in span and 9.2m in width in the form of a box-beam made of GFRP honeycomb plates was built in Beijing, which was the first trial to use FRP in bridges in China. After about one year’s service, a local depression was observed in the bridge due to the instability of the honeycomb and local buckling. The GFRP beam was then strengthened into a GFRP-concrete composite beam in 1987 and the bridge has performed well till now.

Systematic research on FRP in construction was begun in 1997 when the external bonded CFRP sheets strengthening technique for RC structures was introduced in China. The first test to demonstrate the effectiveness of this new strengthening method was conducted in 1997. Then, a series of experimental studies were conducted at Tsinghua University under the leadership of YE and YUE (Ref. 1-3). With the fundamental research results, FRP began to find its applications more and more in RC structure strengthening. It is estimated that about 600,000m^2 of FRP sheet was used in 2003. In 1998, a sub-committee of FRP in construction was founded under the Chinese Civil Engineering Association. After that, there has been more and more research on FRP strengthening of structures. Figure 1 shows the growth in the number of technical papers on FRP in construction published in Chinese journals from 1997 to 2003. In 2002 and 2003, two key research projects on FRP in civil engineering were supported by the Chinese Science and Technology Ministry and the Chinese National Science Foundation. A design specification for RC structures strengthening with CFRP sheets was published in May, 2003. Now, a design code of FRP in civil engineering with a wider scope of application of FRP in addition to RC structure strengthening is under development and will be finished by the end of 2004.

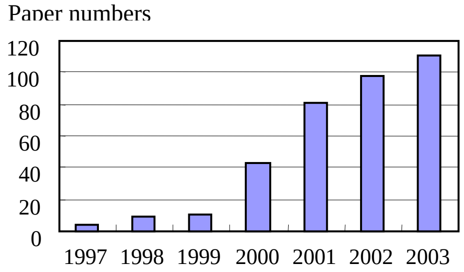


Figure 1. Numbers of Technical Papers Published in Chinese Journals.

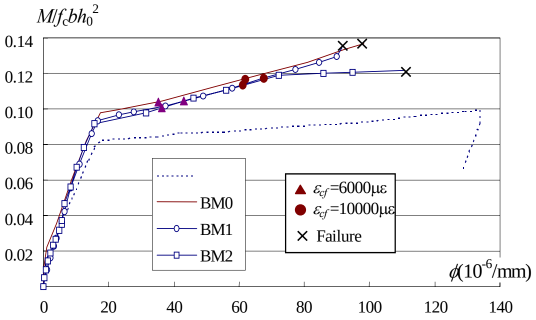
2 RC STRUCTURE STRENGTHENING

2.1 *Flexural Strengthening*

Figure 2 shows the experimental research of RC bridge slab flexurally strengthened with CFRP sheets bonded to the soffit under sustained load. It was found that the initial load before strengthening has only a small influence on the ultimate strength (Ref. 4).

With the initial experimental research, it was found that debonding failure was one of the controlling failure modes. And then tests on fourteen beams, in addition with a series of FRP-to-concrete bond tests, were conducted on the debonding strength, and FRP U-jackets were suggested to increase the flexural debonding strength (Ref. 5). Figure 3 shows that the flexural debonding strength and the deformation capacity can be increased with a uniform arrangement of U-jackets. A thorough theoretical study with the finite element method on the debonding behavior was then undertaken (Ref. 6). A more detailed report on research on debonding is given in another paper to be presented at CICE 2004 (Ref. 7).

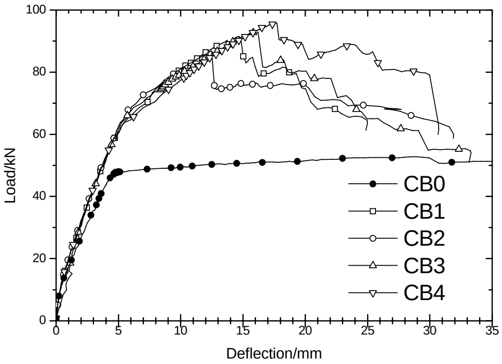
(a) Test set-up



(b) Test results of M-ϕ relation

Figure 2. Test of RC bridge slabs strengthened with CFRP sheets under sustained load

(a) Test Set-up

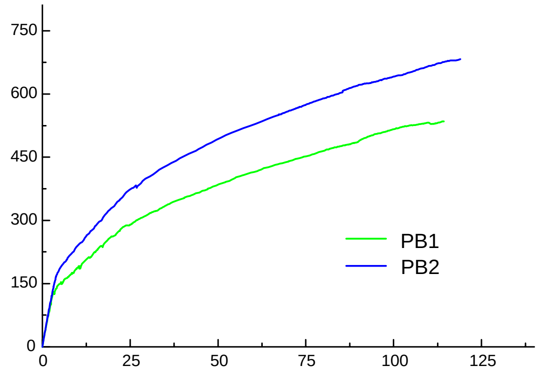


(b) Load-Deflection Relations

Figure 3 Flexural Debonding of CFRP-strengthened RC beams with U-jackets for anchorage

It is known from a lot of research that the strength of FRP can only be effectively developed after the yielding of tensile steel reinforcement in RC beams for flexural strengthening. And it is naturally to apply prestressed technique for flexural strengthening and a device to apply prestressing to FRP sheets was developed in 2003 (Ref. 8). Then, seven full scale beams strengthened with prestressed CFRP sheets, including five RC beams and two PC beams, were tested. Figure 4a shows the prestressed CFRP sheets before bonding to the bottom of the beam, and Figure 4c shows a comparison of the two PC beams, in which PB1 is the one strengthened with the conventional method and PB2 is the one strengthened with prestressed CFRP sheets.

(a) Prestressed CFRP sheet before bonding to the bottom of the beam and the test set-up



(b) Comparison of load-deflection relations

Figure 4 RC Beams Strengthened with Prestressed CFRP Sheets

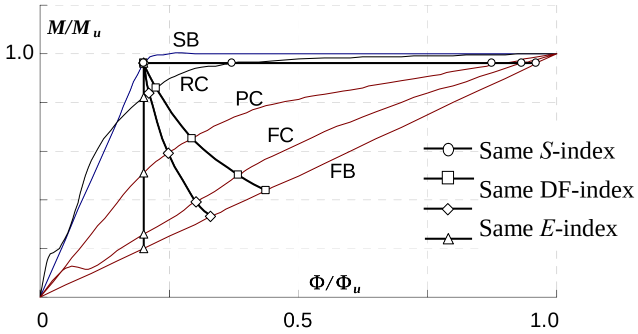
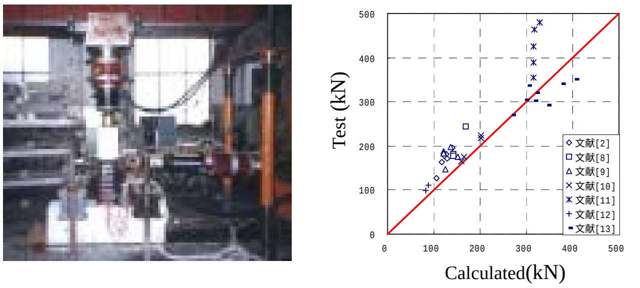


Figure 5 Comparison of design levels using different design indices

To achieve the same safety degree as ordinary RC and steel beams, the design indices for strength, ductility and deformability for different load-deformation patterns obtained from different compositions of material were studied. Figure 5 shows the comparison of design levels using different design indices for normalized M-ϕ relations of steel, RC, PC, FRP-concrete and FRP beams, in which $S=M_u/M_d$ is the strength index; $D=\phi_u/\phi_d$ is the ductility index; $E=E_u/E_d$ is the energy index; $DF=(M_u/M_d)(\phi_u/\phi_d)$ is the deformability index. It was concluded that the deformability index and the energy index are reasonable for use to achieve the same safety degree for FRP and FRP-concrete beams as the RC and steel beams. Based on this design philosophy, the design criteria based on the reasonable design index is used for flexurally strengthened RC beams and the other of FRP application in construction.

2.2 *Shear Strengthening*

In 1998, seven specimens of RC columns strengthened by wrapping CFRP sheets were first tested at Tsinghua University to investigate the shear strength enhancement (Figure 6a, Ref. 9). In the tests, the strains and their distributions in the CFRP sheets were carefully studied to determine the contribution of CFRP to the shear strength. It was found that the amount of CFRP, shear-span ratio and axial load ratio have effects on the contribution of CFRP to the shear strength (Ref. 9-11). Based on the analysis of test results, a simplified calculation formula to determine the contribution of CFRP to the shear strength is suggested (Ref.12). Figure 6b shows the comparison of the calculated results and the test results.

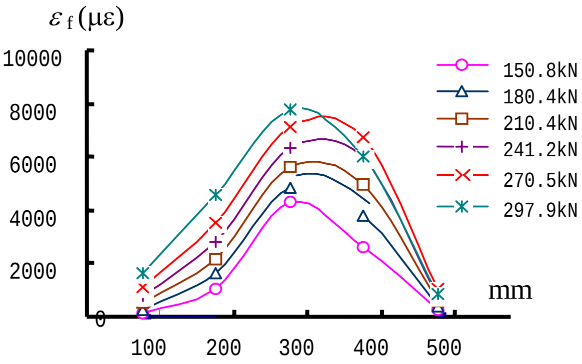


(a) Test set-up

(b) Comparison of calculation results with test results

Figure 6 Shear strengthening of RC column

(a) Failure pattern



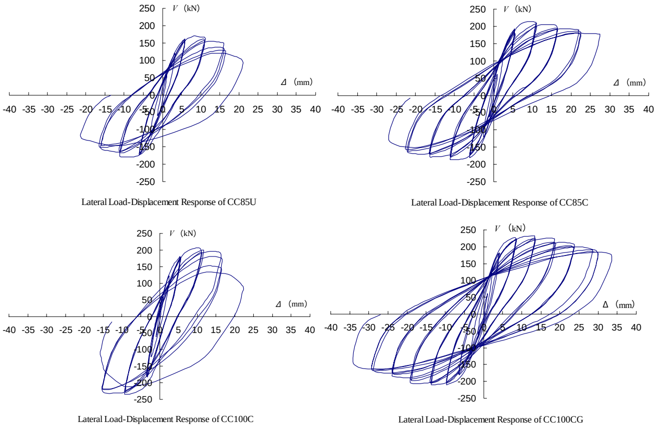
(b) The strain distribution in FRP

Figure 7 Debonding failure of RC beams shear strengthened with GFRP U-jackets

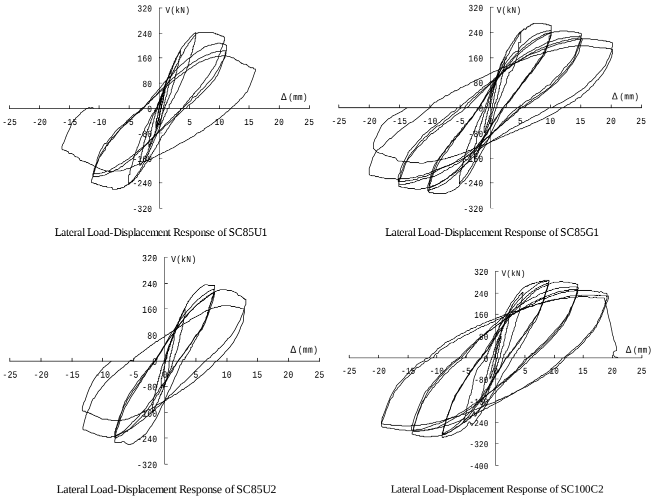
For RC beams, U-jacket bonded strengthening is always used in construction and debonding is the main failure mode. In 2002, 15 beams were tested to investigate the shear debonding strength (Ref. 13). The strain distribution and its development in the FRP sheets were carefully studied to obtain the shear contribution of FRP when shear debonding occurs. Figure 7a is a photograph of shear debonding failure of GFRP U-jackets. Figure 7b shows the strain distribution and development in the GFRP sheets. Based on the test results and finite element analysis (Ref. 14), it was found that the shear contribution of FRP U-jackets only depends on the bonded area and the FRP-to-concrete interfacial shear strength. It was found that the shear-span ratio has some influence on the strain distribution, and the stiffness of FRP sheets has less effect on the shear contribution of FRP.

(a) Circular columns (b) Square columns

Figure 8 Test set-up for RC columns under high axial load and cyclic lateral load



(a) Circular columns



(b) Square columns

Figure 9 Load-displacement hysteresis relations of RC columns under high axial load and cyclic lateral load

2.3 *Seismic Strengthening of RC Columns*

In 1998, eight specimens of RC columns, including two strengthened after being loaded to yield level with some damage and one strengthened under a sustained axial load, with insufficient hoops according to the current Chinese seismic design code were tested under constant axial load and lateral cyclic load at Tsinghua University to investigate the improvement of seismic performance by wrapping CFRP sheets (Ref.15-16). The ductility enhancement with the confinement of CFRP sheets was studied by the strain development and distribution in the CFRP sheets. Based on the experimental research, it was found that the strains in the wrapped CFRP sheets were mainly induced by the expanding concrete after the yielding of the columns. An equivalent confinement factor of the wrapped CFRP sheets was proposed to make up for the deficiency in the amount of steel hoops.

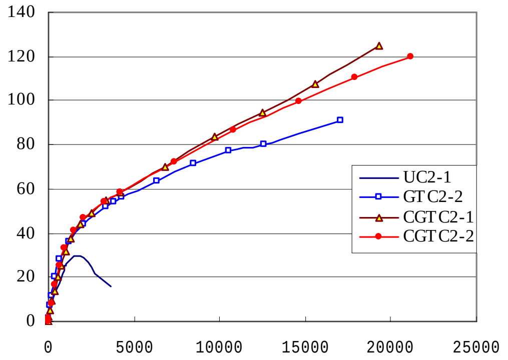
In the Chinese seismic design code, the axial load is limited for RC columns to ensure sufficient ductility. The limitation of the axial load is related to the amount of steel hoops. There is a demand in construction to increase the axial load limitation with the confinement of FRP for existing columns. A series of experiments, including six circular RC columns and seven square RC columns were conducted in 2003 under high axial load-to-concrete strength ratio (σ_c/f_c=0.7-1.0) and cyclic lateral loads (Figure 8-9). Based on the experimental results, the relationship between steel reinforcement confinement and FRP confinement was calibrated, and a simple expression was proposed. As a result, the design method of FRP confinement can be easily implemented into the design code for RC columns.

2.4 *Compressive Stress-Strain Behavior of FRP-Confined Concrete*

The compressive behavior of concrete confined by FRP and hybrid FRP jackets and tubes, including round, square and rectangular sections under uniaxial compression were researched in several universities in China. Figure 10 shows some photographs of specimens tested at Tsinghua University and some test results. A design-oriented stress-strain relation considering the effects of section type, size ratio and initial axial load ratio was suggested based on the test results.

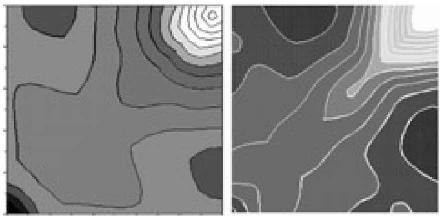
In order to investigate the behavior of square concrete columns confined by FRP sheets, finite element analysis was used. The FEA method can effectively simulate the behavior of square columns confined by FRP sheets when a proper numerical model is adopted. Based on the test and FEA results, the stress distributions and the stress development were obtained (Figure 11a). And the strong constraint area at the corners, the weak constraint area at the edges and the average constraint area in the centre were determined (Figure 11b). These results provide a theoretical understanding for establishing a stress-strain model. Figure 12 shows a comparison of stress-strain curves from FEA and the test results.

(a) Specimens of confined RC columns: square and rectangular section confined with CFRP and hybrid FRP; GFRP and hybrid C-G-FRP tube

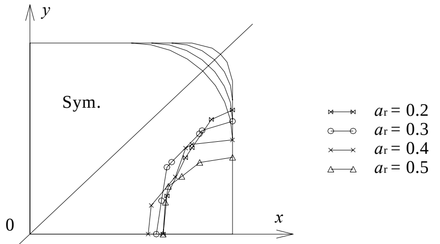


(c) Stress-strain relations of FRP tube confined concrete

Figure 10 Tests on FRP confined concrete



(a) Stress distribution in concrete (darker for lower stresses)



(b) Strong and weak confined regions

Figure 11 FE analysis results

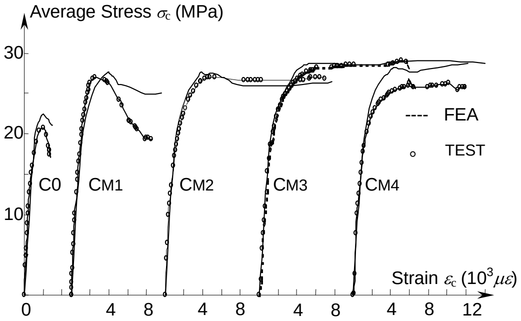


Figure 12 Comparison of stress-strain curves

A new analysis-oriented stress-strain model for FRP-confined concrete has been proposed for circular columns (Ref. 18). In this model the responses of the concrete, the FRP jacket and their interaction are explicitly considered. The key new feature of this model is a more accurate and widely applicable lateral strain equation based on careful interpretations of test results of unconfined, actively confined and FRP-confined concrete. Independent test data were compared with predictions of the proposed model to demonstrate its accuracy, as shown in Figure 13.

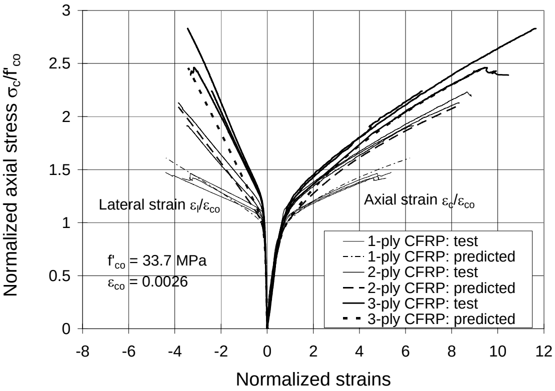


Figure 13 Comparison with test results of CFRP-wrapped specimens

2.5 *Others*

The research on the strengthening of other RC structural elements with FRP sheets and plates in China includes two-way slabs, torsional members and beam-column joints. There has also been research on RC beams strengthened using external prestressed CFRP strands and fatigue behavior of RC beams strengthened with CFRP sheets and prestressed CFRP sheets.

3 STRENGTHENING OF OTHER KINDS OF STRUCTURES

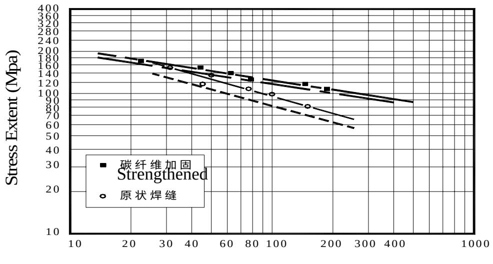
3.1 *Steel Structures*

To increase the fatigue strength of steel beams, a series of experimental studies on the strengthening of steel structures with CFRP were conducted at the National Engineering Technique Research Center of Industrial Buildings since 2001. The tensile tests showed that the tensile strength can be increased by 8~21% with different amounts of CFRP. Figure 14 shows welded tensile specimens and a comparison of the S-N relation under fatigue cyclic loading. An increase in the fatigue strength was also obtained in a steel beam in which CFRP sheets were bonded to the round corners at the support of the steel beam.

3.2 *Masonry Structures*

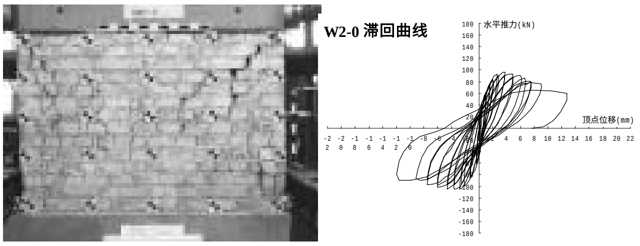
About sixty percent of the masonry buildings in China were built about 30 years ago and some were built more than 100 years ago. Many of them do not meet the requirements of the current design requirements, especially the seismic resistance of the masonry walls. About 40 masonry walls strengthened with GFRP and CFRP sheets were tested under cyclic lateral load in the wall plane to investigate seismic resistance behavior in China. Figure 15 shows the experimental research conducted at Tsinghua University. It was found that the seismic shear strength of masonry walls can be increased by the direct tensile stresses developed in the FRP sheets, and in addition, the integrity of the wall can be enhanced.

(a) Welded tensile steel specimens

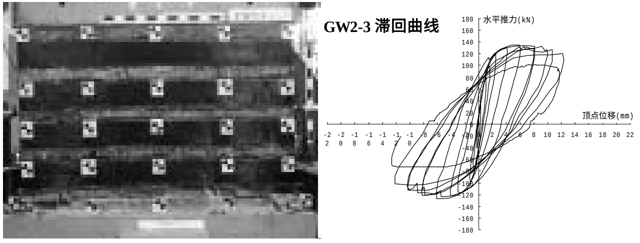


(b) Comparison of S-N relation

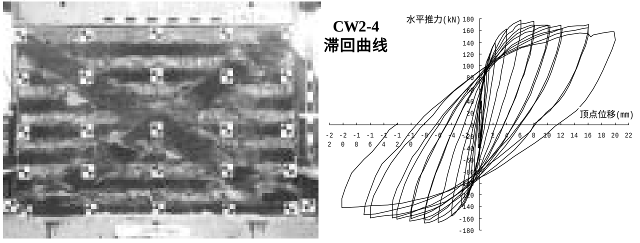
Figure 14 Fatigue behavior of tensile steel specimens



(a) W2-0

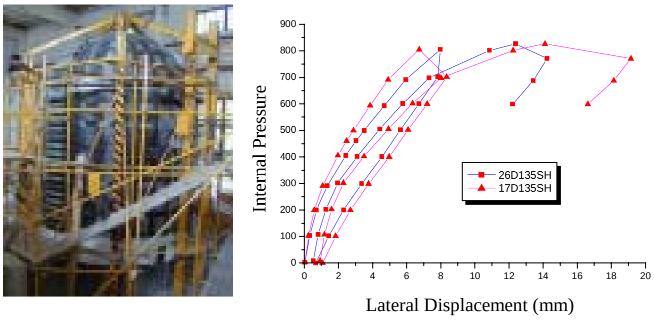


(b) CW2-3



(c) CW2-4

Figure 15 Test of Masonry Walls Strengthened with FRP Sheets



(a) Test model (b) Test curves of internal pressure and lateral displacements

Figure 16 Test of containment shell structure of nuclear power station

3.3 *Special Structures*

Figure 16 shows a test of a containment shell structure of a nuclear power station strengthened with CFRP sheets conducted by the National Engineering Technique Research Center of Industrial Buildings. The one-tenth scale shell structure model was first loaded to failure under internal pressure and then strengthened with CFRP sheets. It was shown that the capacity can be recovered and a little increased to the level of the new one.

4 RC STRUCTURES WITH FRP BARS AND PRESTRESSED FRP TENDONS

Research on RC structures using FRP bars began at Southeast University, Nanjing, in 1999, and then at Tongji University, Shanghai. More than 40 beams were tested to determine the flexural behavior and to establish the flexural strength. To obtain high performance, Southeast University began to study RC beams prestressed with FRP tendons and developed some anchorage devices for prestressed FRP tendons. The design methods are now well developed, but there has been no application so far, because there is not much demand in construction compared to FRP strengthening.

(a) Chenjiawan bridge

Jiaoyuan Bridge

Figure 18 GFRP footbridges in Chongqin

5 ALL FRP STRUCTURES AND FRP-CONCRETE COMPOSITE STRUCTURES

5.1 *GFRP Bridges*

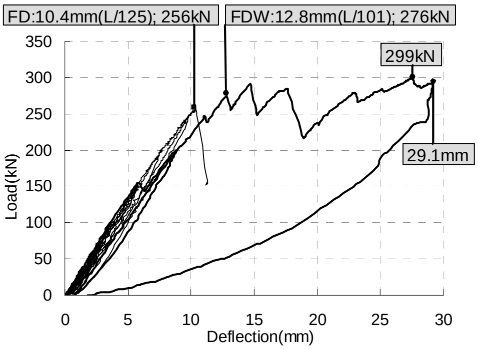
Besides the first GFRP highway bridge built in Beijing in 1982, about seven GFRP footbridges were completed in Sichuan province from 1986 to 1993. Figure 17 shows two of them built in Chongqin.

5.2 *FRP Bridge Deck*

In 2001, a reserch project on FRP bridge decks was undertaken at Tsinghua University. The initail test results showed that delamination and local buckling were the controlling failure modes. To enhance the deck’s performance, the use of outside filament winding was proposed. Figure 19 shows obvious improvement as a result of filament winding. A pseudo-ductile behavior can be achieved by outside winding reinforcement. Based on the initail test results, an FRP deck product for traffic bridges was designed as shown in Figure 19.

(a) FRP deck without outside filament winding

(b) FRP deck with outside filament winding

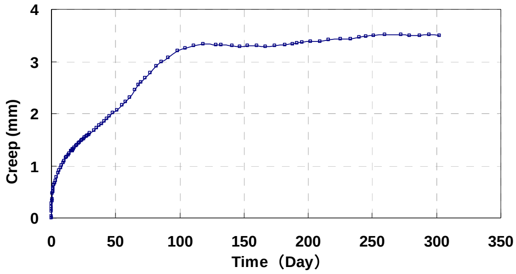


(c) Comparison of load-deflection of FD and FDW

(d) FRP deck product

Figure 19 FRP bridge deck for traffic bridges

(a) Test set-up



(b) Creep deformation

Figure 20 Long term test of FRP deck

5.3 *FRP space structures*

Due to its favorite properties of lightweight and high strength, it is reasonable to use FRP to construct super span space structures. Two types of all FRP super-span space structures are now under research at Tsinghua University. One is the latticed space structure using FRP tubes. Figure 12 shows CFRP tubes used to study their mechanical behavior under axial tensile and compressive forces. A linear behavior was found in the tests until debonding or buckling failure occurred.

(a) CFRP tubes for latticed space structures

(b) Debonding failure under tension

(c) Debonding failure under compression

(d) Local buckling failure

Figure 20 CFRP tubes for space truss structures

Another innovative form of FRP super-span space structures is the FRP woven web structure (FRP WWS). A model is shown in Figure 21. In the FRP WWS, the high-strength FRP strips are woven like bamboo strips in a Chinese bamboo mat to form a plane web. The outer and the inner ring beams are provided to anchor the FRP strips, which are initially prestressed to establish suffcient stiffness. The low self-weight, high tensile strength and corrosion-resistance of FRP strips can be fully utilized in an FRP WWS. In addition, a significant amount of damping can be expected to arise from friction at joints between FRP strips. Special architectural configurations can be achieved by employing regular weaving patterns.

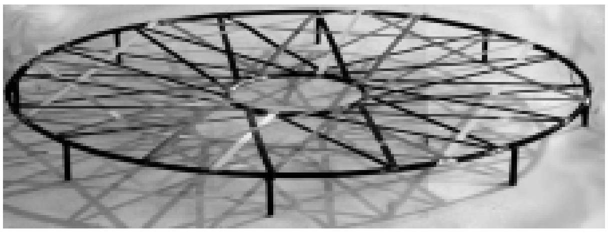


Figure 20 A model of the FRP woven web structure

5.4 *Concrete Filled FRP Tubes*

More than 40 concrete filled GFRP tube columns were tested to determine their static and seismic behavior at Tongji university since 1999. The ductility of the columns was much increased with the confinement of GFRP tube. It was found that GFRP tubes made with fibers in 45 degrees had pseudo-yielding properties under compression. A hybrid tube of GFRP and CFRP has been used in the research on compressive behavior of confined concrete at Tsinghua University in 2003, as shown in Figures 10c and 10d.

6 DESIGN SPECIFICATIONS AND STANDARDS

The development of the first design and construction specification for CFRP strengthening of RC structures began in 1998. The specification was formally approved by the Chinese Construction Standard Committee in May, 2003. Two material product standards, for CFRP sheets and resins respectively, were also published. With the increased field applications of FRP in civil engineering and based on the researches in recent years, a code of FRP application in civil engineering has been under development since 2002. The contents of the code are as below.

(1) FRP materials: CFRP, GFRP and AFRP and their products, such as FRP bars, strands and tubes, are included. The standard mechanical properties should have a reliability of 95% based on more than 15 standard tests. And lower bounds are imposed for each kind of FRP materials and the corresponding mechanical properties.

(2) Strengthening of RC structures: Flexural strengthening of beams and slabs with external bonded CFRP sheets and plates, both prestressed and unprestressed. The use of GFRP and AFRP in flexural strengthening is not allowed due to their lower modulus; Shear strengthening of beams and columns; Strengthening of two-way slabs; Strengthening of torsional beams; Seismic strengthening of columns; and Quality control and checking procedures are also provided.

(3) Strengthening of masonry structures: seismic strengthening of masonry walls and a calculation method for the in-plane shear strength is provided.

(4) Strengthening of steel structures: fatigue strengthening and an evaluation method is provided.

(5) Concrete beams reinforced with FRP bars and prestressed with FRP strands.

(6) FRP and FRP-concrete composite structures: concrete filled FRP tubes and FRP slabs.

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