STATE OF THE ART: RESEARCHES AND APPLICATIONS OF FRP IN CIVIL ENGINEERING IN CHINA

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This paper summarizes the researches and applications of FRP in civil in China. It includes structure strengthening with FRP sheet and plates, reinforced concrete structures with FRP bars and tendons, pure FRP structures and bridges, FRP-concrete composite structures and self-monitoring using CFRP. The code of FRP application in civil engineering, which is under editing, is also introduced. The future research topics and projects in China are prospected.

INTRODUCTION

The first research of FRP in civil engineering in China, as the authors known, was a fatigue test of a T section the hanging bridge beam, 6000mm span and 1000mm height, reinforced with GFRP bars made in Tsinghua university in 1958. The propose of the test was intend to use GFRP bars to instead of steel bars due to that there was limit amount of steel in that years in China. But the beam failed in very brittle style with a sudden rupture of GFRP bars, so that the research was not continued. From 1970s, there were some research institutes in China began the research on the GFRP bridge and there were some GFRP bridges were built. Besides, there some researches and application of GFRP water tanks for buildings. But it was until the late of 1990s that the FRP was found its popular application in civil engineering in China when the external bonded techniques of structure strengthening using CFRP sheets became accepted in Chinese civil engineering. And after that, the Chinese engineers began to acknowledge merits of the new building material of FRP, and the researches of FRP in civil engineering in China became more and more since then. In 1998, a committee of FRP and application was founded in Association of Chinese Civil Engineering (ACCE). Under the organization of committee, a series research projects were undertaken. This paper introduce the state-of-the-art of the researches and application of FRP in civil engineering in China.

STRUCTURE STRENGTHENING

RC Structures

Same as the other countries, the most application of FRP in civil engineering in China is the RC structure strengthening using external bonded CFRP sheets or plates. The first test and application was in 1997, which was conducted by National Engineering Technique Research Center of Industrial Building (NETRCIB). After that, many researches on this new technique were taken out in China. From 1997 to 1999, the researches were mainly to demonstrate the effectiveness of the strengthening method.

Under the support of Chinese Science and Technology Bureau, a series of experimental researches on flexural strengthening of RC beams and slab, shear and seismic strengthening of RC columns were conducted in Tsinghua university and NETRCIB to established the design method for the RC structure strengthening with CFRP sheets and plates. The design method was established based on the Chinese design approaches of RC structures, i.e., the limit state design philosophy was adopted. The contribution of CFRP to the strength of RC members was determined by its strain development at the corresponding limit state and a maximum allowing strain for CFRP, equal to 2/3 rupture strain of CFRP sheet and plate, is limited considering the elastic brittle material behavior of CFRP.

Figure 1 is the test photo of RC bridge slab strengthened with CFRP sheet under sustaining load. The flexural strengthening with bottom bonded CFRP sheets showed that the plane section assumption is also suitable, and the strain development of CFRP sheets can then be determined based on the assumption. The test and parameters analysis also show that the strengthening effectiveness become less when the original steel reinforcement or the CFRP amount are too large. There was also a suggestion that the flexural strengthening was effective with side bonded CFRP sheet in the tensile zone of the RC beam section in Tongji university, Shanghai, China.

Figure 1 Test of RC bridge slab strengthened with CFRPsheets under

Figure 2 Test set of RC column strengthened with CFRP sheets

Figure 2 is the test set photo of shear and seismic strengthening of RC columns with CFRP sheet. In the column tests, the strain value and distribution in CFRP were studied to determine the contribution of CFRP to the shear strength and confinement at maximum loading. There were total about 75 column specimens strengthened with CFRP, GFRP and AFRP, conducted in six universities in China. The concrete strength was up to 78.2MPa, the shear span ratio was from 5.1 to 1.0, and the axial force ratio was from 0.13 to 1.29.

Based on the series researches and some design guideline of other countries, the Chinese committee of FRP and application edited the first specification for the RC structure strengthening with CFRP sheets and plates in China in December, 1999. Figure 3 shows the comparison of the the calculated shear strength suggested in the specification to the test results for 32 column specimens failed in shear.

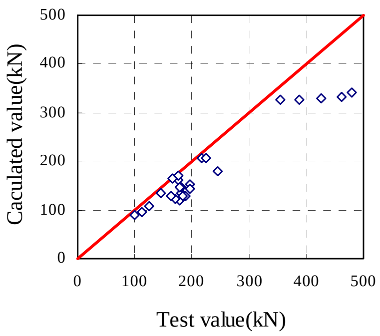


Figure 3

Figure 4 Debonding strength test and failure photos

With the publication of the specification and continues researches in some other research institutes and universities, the effective strengthening technique of external bonded FRP sheets or plates for RC structure strengthening was accepted by Chinese engineers and become used more and more widely. It is estimated that the usage amount of CFRP sheets used in structure strengthening is about 500,000 m^2 in 2002.

In editing the specification, it was found that the debonding strength between CFRP and concrete was important to control the CFRP strain development. Then, a series researches on debondng strength and debonding capacity for flexural and shear strengthening of RC beams were condeucted in Tsinghua university and NETRCIB. Figure 4 is a failure photo of debondng strength tests; Figure 5 is a photo of debonding failure of flexural strengthening of bottom bonded CFRP sheets with U-type CFRP sheets anchorage; and Figure 6 is a photo of debonding failure of shear strengthening using U-type GFRP sheets.

With the series researches of experiment and finite element analysis on debonding behaviors, the debonding strength and capacities were suggested. Figure 7 shows the comparison of test, analysis and suggested for shear stress distribution between the interface of bottom bonded CFRP sheets and concrete under debonding limit state. Figure 8 is the comparison of calculated results of suggested debonding shear strength with U-type FRP strengthening to the test results of 30 experiments finished in China and abroad.

Figure 5 Debonding failure of flexural strengthening with U-type anchorage

Figure 6 Debonding failure of shear strengthening using U-type GFRP

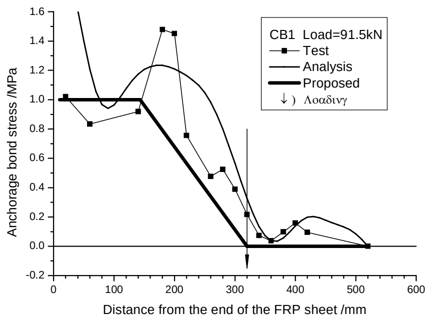


Figure 7 Shear stress distribution between CFRP sheets and concrete

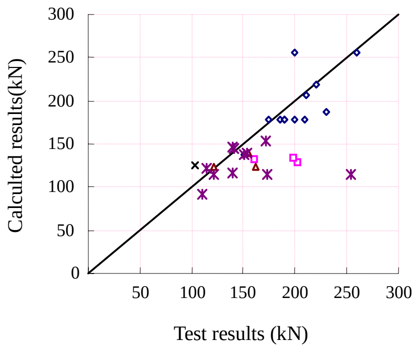


Figure 8 Comparison of calculated results and test results of shear strength for debonding failure using U-type FRP

The basic compressive behaviors of confined concrete by FRP and hybrid FRP jackets, including round, square and rectangular sections, were researched in several universities in China. Figure 9 is a photo of square section columns confined by CFRP and GFRP, which was tested in Tsinghua university. There were also research reports and publications about strengthening with FRP sheets and plates for two-way slabs, torsion members and beam-column joints.

Figure 9

Steel Structure

Since 2000, series experimental researches on steel structure strengthening with CFRP were conducted by NETRCIB. The researches included:

(a)Axial tensile test of steel plate (see Figure 10). Thirteen tensile tests showed that the yielding strength could be increased 8~21% for deferent amount CFRP.

(b)Static and fatigue axial tensile test of cross section specimen with K-type welding. The test showed that the fatigue strength could be effectively increased under high stress changes and the fatigue cracks were delayed after strengthening with CFRP.

(c)Fatigue strengthening of round corner at the support position of steel beams (see Figure 11). Fifteen tests showed that the fatigue life could be increased about 50%.

Figure 12 shows a steel roof truss structure strengthened with CFRP sheets. The load of the truss was increased due to usage changing, which induced a stress increase in the upper and lower chords.

Masonry Structure

There is about 60 percent masonry structure of buildings in China, which were built about 30 years ago and some were more than 100 years ago. Many of the masonry buildings are not meet the requirements of current design code, especially the aseismic capacities. After the bonded FRP strengthening method became popular for RC structure, it naturally has the demand to apply it for the strengthening of masonry structures. The main research on the masonry structure strengthening with FRP is the seismic strengthening of masonry wall under cyclic lateral load in the wall plane. There were about 40 tests of masonry wall specimens finished in four universities. Figure 13 shows a photo of masonry wall test strengthened with GFRP conducted in Tsinghua university, and Figure 14 shows the comparison of the lateral load-displacement hysteresis relations of the strengthened wall to that of unstrengthened one.

Figure 10 Tensile test of steel plate strengthened with CFRP

Figure 11 Fatigue test of steel beam strengthened with CFRP at the support

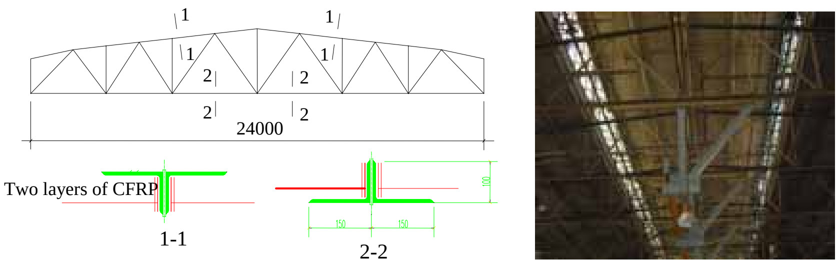


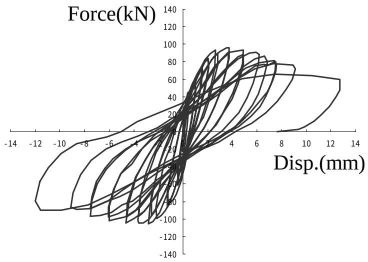
Figure 12 Application of CFRP sheet in a steel roof truss structure

Figure 13 Masonry wall strengthened with GFRP

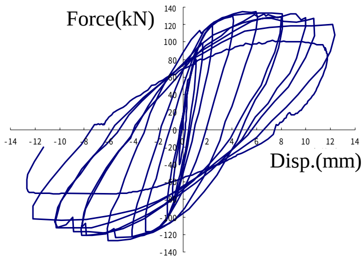
Figure 15 Test of safe shell structure of nuclear power station

Special Structure

Figure 13 shows a test of safe shell structure of nuclear power station strengthened with CFRP sheet conducted by NETRCIB. The one tenth scale shell structure model was first loaded to failure under inner pressure and then strengthened with CFRP sheets. The test showed the effectiveness of the strengthening method with CFRP and the analysis is now under going.



Unstrengthened wall



Strengthened wall

Figure 14 Lateral load-displacement hysteresis relations

RC STRUCTURE WITH FRP BARS AND PRESTRESSED FRP TENDONS

The researches of RC structure using FRP bars began in Southeast university, Nanjing, in 1999, and then in Tongji university, Shanghai. More than 20 beams were tested to determine the flexural behaviors and to establish the flexural strength. To obtain high performance, Southeast university began to study the prestressed concrete using FRP tendons and developed some anchorage devices since 2001. Nanjing GFRP institute also developed GFRP and CFRP bars in 2001. The systems including design method are now well developed, but no application till now because of no so much demand from engineering compared to the strengthening with FRP.

PURE FRP STRUCTURES AND FRP-CONCRETE COMPOSITE STRUCTURES

FRP Bridges

The research of GFRP bridges in China began since 1970s. In 1982, a highway bridge with a 20.7m span length and 9.2m width box-beam made of GFRP honeycomb plates was built in Miyun, Beijing, which was the first try to use FRP in bridge in China. The bridge was designed to carry a QI-15 truck load. The bridge was tested in field before opened and showed the feasibility of GFRP for bridge. After some time under service, there happened a local depressing in one deck due to the instability of the honeycomb and a local buckling at the compression part of a web. Thus, it was examined and repaired in 1987, and the GFRP beam was strengthened into a GFRP-concrete composite beam. It is well in service till now.

In 1986, Jiaoyuan Bridge, a single tower cable-stayed footbridge in Chongqing, was completed. The bridge is 50m long with a 27.4m main span. The cables are made from high-strength steel tendons, and the pylon is RC. The superstructure is a box-beam made of GFRP honeycomb sandwiched plates. The weight of GFRP beam is 8.9t, which is only 30% of steel beam and 13% of RC beam. The bridge cost 250,000 Yuan (RMB) and 1,000 Yuan(RMB) per square meter, which is only 36% for a steel bridge. After that, many footbridges completed in Sichuan province, China (see Table 1).

Chenjiawan bridge

Jiaoyuan Bridge

Figure 16

Figure 16 are the pictures of Chenjiawan Bridge and Guanyin Bridge in Chongqin city, China. The GFRP elements in these bridges were made by hand lay-up. All kinds of complicated shapes can be fabricated in this method. However, the quality of lay-up fabrication is depended on the production process, so it is unstable. In 2001, the Jiaoyuan Bridge was repaired and the Guanyin Bridge was demolished because of the large deformations.

Table 1: Some GFRP Footbridges in China

Year	*Name and Location*	*Introduction*	*Length of Beam*	*Width of Bridge*	*Load for Design*
1986	*Jiaoyuan Bridge, Chongqing*	*Single tower cable-stayed bridge, GFRP beam*	27.4m	4.4m	3.5kN/m^2
1988	*Chenjiawan Bridge, Chongqing*	*Half-through rigid spatial frame bridge, 3 spans continuous GFRP beam*	11.2m	4.0m	4.0kN/m^2
1988	*Guanyin Bridge, Chongqing*	*Half-through rigid spatial frame bridge, 4 spans continuous GFRP beam*	9.8m 19.2m	4.2m	4.0kN/m^2
1988	*Footbridge, Luzhou, Sichuan*	*Single span simple supported GFRP beam*	13m	4.0m	3.5kN/m^2
1992	*Huashan Bridge, Panzhihua, Sichuan*	*Half-through X arch bridge, 4 spans continuous GFRP beam*	24.0m	3.0m	3.5kN/m^2
1993	*Chuanmian Bridge, Chengdu, Sichuan*	*Unsymmetrical A-shaped arch bridge, GFRP beam*	10.1m	5.0m	4.0kN/m^2
1993	*Xiangyang Bridge, Chengdu, Sichuan*	*Unsymmetrical A-shaped arch bridge over a river, GFRP beam,*	50m	4.0m	4.0kN/m^2

FRP space structure

For FRP is lightweight and high strength material, it is reasonable to use FRP to make super large span space structure. Figure 17 shows the CFRP tubes developed for the research of space truss structure in Tsinghua university.

GFRP breakwater

The flood is the main hazard in China, and many manpower and sandbags are needed to build the breakwaters in rain season every year. To alleviate the manpower to build the breakwaters, a FRP sandwich panel breakwater is developed in Beijing FRP institute, as shown in Figure 18. Because of the lightweight, the FRP breakwaters can be shipped and installed very quickly when the flood is coming. After the flood, the FRP breakwaters can easy be uninstalled and stored, and no need to care the corrosion.

Figure 17 CFRP tube for space structure

Figure 18 GFRP breakwater

Concrete Filled FRP Tubes

More than 40 concrete filled GFRP tube columns were tested to determine the static and seismic behaviors in Tongji university since 1998. The ductility of the columns was much increased with the confinement of GFRP tube. It was found that the GFRP tube made in 45 degree had a pseudo-yielding properties under compression. A hybrid tube with GFRP and CFRP was prepared for the research on compressive behaviors of the confinement concrete in Tsinghua university.

SELF MONITORING OF CFRP

Because of the electric conduct property of CFRP, it can be used in self structure monitoring by detecting the changes of electric resistance. Figure 18 shows the changes of electric resistance in CFRP sheets with the deflection of a RC beam strengthened with bottom bonded CFRP sheets. The test was done in Tsingua university in 2000. The load-deflection relation is also shown in Figure 19. It can be seen that the electric resistance in CFRP is decreased as deflection increasing before the yielding of the steel reinforcement, but begin to increase as deflection increasing after the yielding.

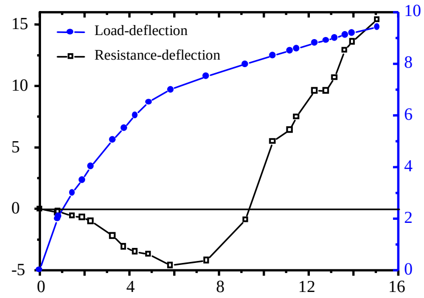


Figure 19

DESIGN SPECIFICATIONS AND STANDARDS

The first design and construction specification for CFRP strengthening in RC structure was published in the end of 1999. And two material product standards, CFRP sheet and resin, were also published at same time. With the increased application fields of FRP in civil engineering in China and based on more researches, a code of FRP application in civil engineering is under editing. The code includes FRP material, structure strengthening and repairing of RC, steel, masonry and wood structure, concrete structure elements with FRP bars and prestressed FRP tendons, and FRP-concrete composite structure elements. The code will be finished in the end of 2003.

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REFERENCES

Because of too many references and the limited pages, the references are not listed here.