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Case Study on a Historical Building Structure Strengthened by CFRP

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ABSTRACT: Through in-situ inspection, the information such as the material strength, structural member dimension, damage situation, and the dynamic characteristics of the structural system for a historical building, Shanghai post office building, are acquired. Based on the information, the mechanical behavior of the building structure is assessed and the suggestion of structural strengthening is proposed. To find out the optimum strengthening method for reinforced concrete beams or slabs, tests for low-strength concrete beams strengthened by CFRP sheets were conducted. Test results show that it is possible to enhance the bending and shearing capacity of a low-strength reinforced concrete flexural member by gluing the CFRP sheets with proper construction measures. The situation of the building after the construction shows that the strengthening methods proposed by the authors are effective and applicable.

1 INTRODUCTION

Shanghai post office building is located near Suzhou River in Shanghai, and takes the shape of a "U" (Figs. 1, 2). It was built in 1924 and it has been used as a post office till now. The reinforced concrete building of four storeys overground and one underground covers an area of 6400m^2, while the construction area is 25294m^2. The box foundation is a reinforced concrete structure as well as the turret in the middle of the building. Shanghai post office is protected by Shanghai municipal government for its distinguished classic British building style from 1989 and under national protection subsequently.

During the long service life, the structure suffered different kinds of actions, loads and environments. Many structural beams and slabs have cracked. Most of the steel bars inside concrete corroded. In 2001, the owner of the building planed to change the usage of some rooms, add a glass roof at the middle of the building to form an exhibition space (Fig. 2b), and set up a new central air conditioner system inside the building. But they faced a big problem: How can they protect this historical building and take full advantage of it at the same time? To help the owner of the building to solve this problem, the authors did three things: in-situ inspection and assessment of the building structure; experiment study of low-strength concrete beams strengthened with CFRP sheets; strengthening design and construction. The detail of the work will be introduced in this paper.

2 INSPECTION AND ASSESSMENT

2.1 *Survey of building drawings*

All of the drawings of the building were surveyed firstly through in-situ inspection. The south elevation and the forth structural plane of the building are shown in Fig. 2. From the surveyed drawings, it can be seen that reinforced concrete slabs, beams and columns form the structural system of the building. The vertical bearing system mainly consists of reinforced concrete columns. The reinforced concrete walls of the lobby in the northeast and 23, 35 axis are all cast in site as well as the walls of the turret in the southeast corners and all the staircases (Fig. 2b).

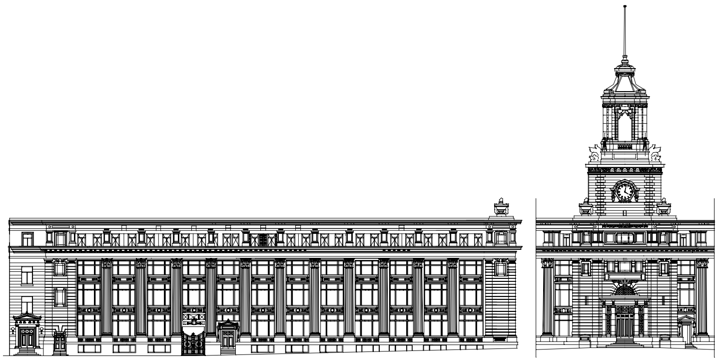
The structure is similar to a frame-shear wall system which is widely used in high-rise buildings nowadays. But the layout of the walls did not follow the principle of frame-shear wall systems.

The raft foundation of the building has a reinforced concrete box-section. The thickness of the upper slab is 114mm, while the lower slab has the range of 191-267mm. The reinforced concrete foundation beams between the upper and lower slabs are orthogonal.

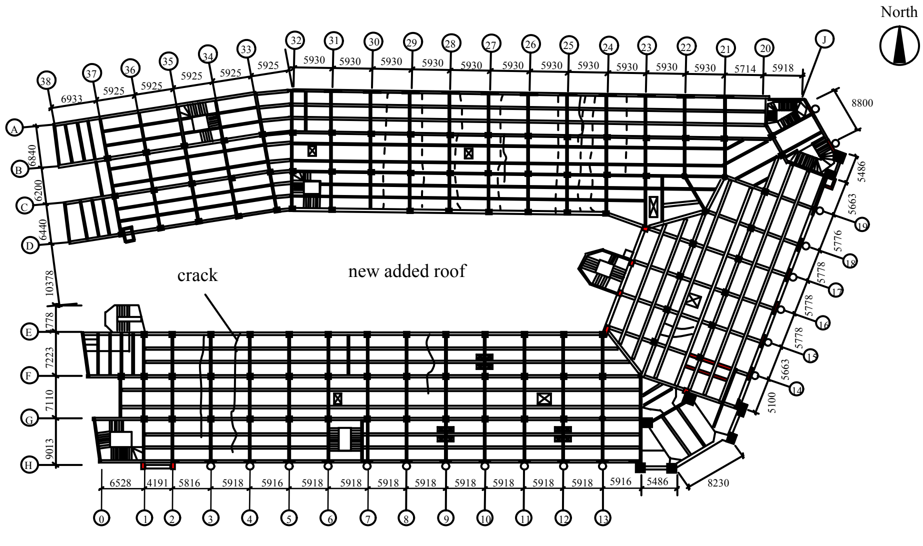
(a) South elevation view before strengthening

(b) South elevation view after strengthening

Figure 1 : Building of Shanghai post office



(a) South elevation of the building



(b) Structural plane of the forth storey

Figure 2 : Elevation and plane drawings of the building

2.2 State and performance of the building structure

During the inspection, cracks have been found in the area of 1-4-E-H on the floor surface of bottom storey and the upper and lower surface of the floor in the other stories. The cracking situation is especially severe in the north part of the building, where the maximum width of the crack reaches 1.5mm (Fig. 2b). Most of the cracks on the floor slab developed in the transverse direction of the building. Cracks were found on beams also (Fig. 3a).

The uneven settlements of the building which were obtained using the SOKKIA C40 high precision level are shown in Fig. 4. The results show that the lowest point located in the turret in the southeast of the building. The settlement trends of the south part of the building and north part of the building are all bending upward, which may cause the floor slabs cracking in south-north direction (Fig. 2b).

The steel bars inside concrete corroded severely, especially in the area of 6-7-E-H of the base room. Some of the steel bars inside the stair beams in the southeast corner of the turret are corroded as well as the bars under the windows in the third storey of the turret. The situation is also severe in the skylight beams and columns, where the longitudinal cracks appear. The concrete on the surface of some parts of the members are spalling and the bars are revealed (Fig 3b).

Based on the characteristics of the building and the in-situ inspection conditions, 6ϕ100 cylinder samples were taken out from the concrete slabs, while 9ϕ100 cylinder samples from the concrete columns. The test results show that the maximum carbonization depth of the concrete is bigger than 64mm, beyond the protective cover.

The ultrasonic-rebound combined method was chosen to evaluate the strength of the concrete. The evaluation results show that the cubic compressive strength values of the concrete of the basement, the first floor, and the second floor are 14.5MPa, 14.0MPa and 12.4 MPa respectively, and the value of the cubic concrete compressive strength for the third and the forth floor is between 10.0MPa ~ 18.4MPa.

(a) Cracks (b) Corroded bar

Figure 3 : Carks on a beam and corroded bar in a beam

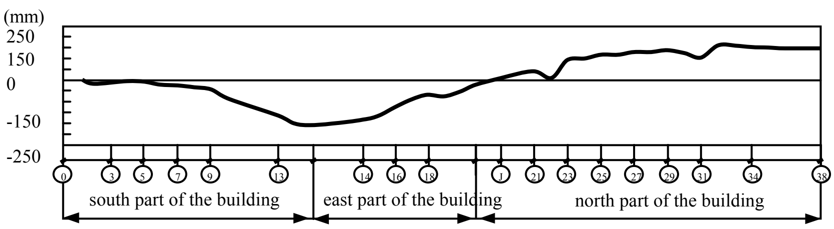


Figure 4 : Uneven settlements of the building

Dynamic parameters of the structure such as the natural frequencies and the damping ratios were identified using the method of random ambient excitation and the modal analysis technology of transfer function (Tab. 1).

Table 1: Natural frequencies and damping ratios of the structure

	Method	Direction	T_1 (s)	T_2 (s)	T_3 (s)
Frequencies	Identified through in-situ test	west-east	0.388	0.129	0.101
		north-south	0.425	0.140	0.106
	Calculated as a frame structure	west-east	0.355	0.111	0.062
		north-south	0.341	0.106	0.060
	Calculated as a frame-shear wall structure	west-east	0.324	0.103	0.059
		north-south	0.310	0.099	0.052
Damping ratios	Identified through in-situ test	west-east	0.053	0.031	-
		north-south	0.054	0.035	-

2.3 Analysis of structural behavior

Based on the information of in-situ inspection and survey, the natural frequencies of the structure were calculated taking the building as a frame structure and a frame-shear wall structure respectively. The calculation results are listed in Tab. 1. Comparing the calculation and the in-situ testing results, it can be seen that the model of the frame structure is more suitable to be used to analyse the mechanical behavior of the structure.

According the results of structural analysis using frame structural model, it was concluded that some of the beams, columns and slabs need to be strengthened to meet the retrofit requirements of the building owner.

3 EXPERIMENT STUDY OF LOW-STRENGTH CONCRETE BEAMS STRENGTHENED BY CFRP

CFRP materials have been widely used in the strengthening of concrete structures due to their extraordinary behavior comparing with other traditional strengthening materials. A lot of research results on the behavior of concrete structures strengthened with CFRP materials have been published all over the world in recent years (Gao 2002, Meier, et al. 1991, Ross, et al. 1999, Teng, et al. 2004, and Ye, et al. 2003). Gluing or wrapping CFRP sheets on the surface of the members is chosen as the major method to strengthen the Shanghai post office building.

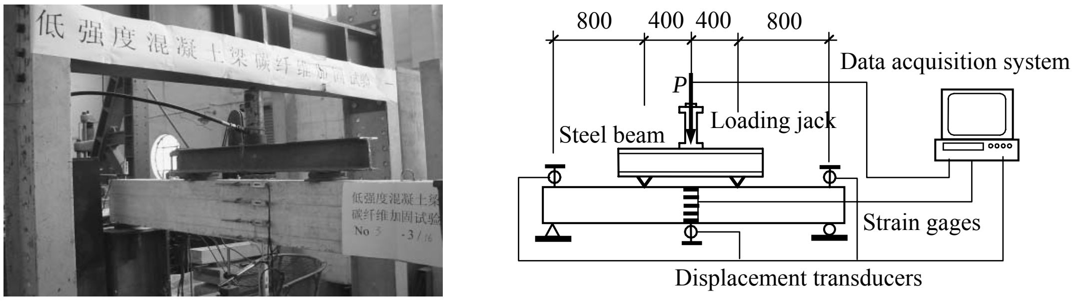
Different from the normal engineering applications, the concrete strength of the building is rather low according to the results of the in-situ inspection. It is not allowed to strengthen the reinforced concrete beam in which the cubic compressive strength of the concrete is less than 15MPa with externally bonded CFRP sheets according to Chinese codes (CECS 146, 2003, DG/TJ 08-012-2002). Similar specification can be found in ACI 440. Because of the limited experience on the study of low-strength concrete reinforced beams (usually, the cubic compressive strength of the concrete is less than 15MPa), it is significant to make an extensive study on the behavior of low-strength reinforced concrete structural members strengthened with CFRP materials. The main purpose of the study is to verify and find out the optimum strengthening method.

16 low-strength reinforced concrete beams were designed and constructed to study the flexural behaviour. The testing set-up and the strengthening method of the beam are shown in Fig. 5 and Fig. 6. The details and the flexural behavior of testing beams are listed in Tab. 2. 14 low-strength reinforced concrete beams were designed and constructed to study the shearing behavior of strengthened beams. The strengthened methods and dimensions of beams are shown in Fig. 7. The details and shearing capacities of the strengthened beams are listed in Tab. 3.

The bending bearing capacity of low-strength reinforced concrete beam can be increased significantly by gluing CFRP sheets externally. With the help of CFRP stirrups, the anchorage condition at the side of CFRP sheets can be improved and the bending bearing capacity of the strengthened beam can be increased more than 90%. Even for a damaged beam, the bending bearing capacity can still be increased significantly by proper strengthening with CFRP sheets.

The deforming behavior of the strengthened beam can be improved significantly with the help of CFRP stirrups. The strengthened beam with CFRP sheets and CFRP stirrups has a large deformation to warn the failure after yielding of steel bars (Fig. 8).

The shearing capacity of a low-strength concrete beam can also be increased by gluing CFRP stirrups in shear spans of the beam.



(a) Loading system

(b) Data acquisition system

Figure 5 : Test set-up

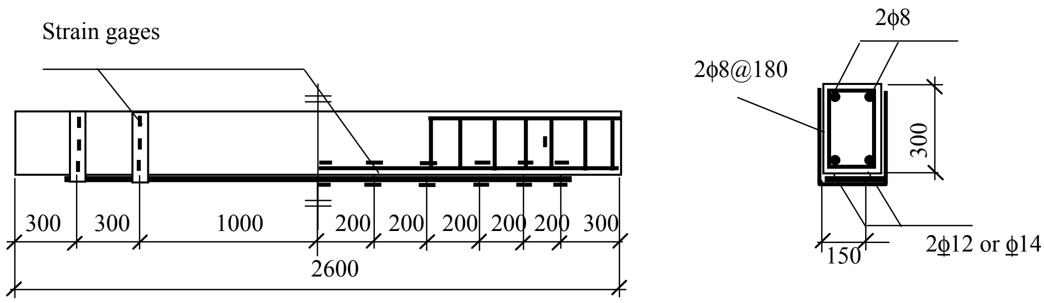
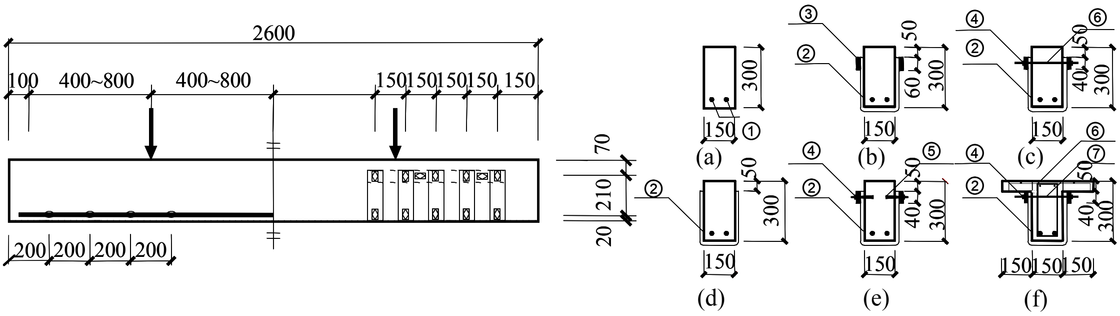


Figure 6 : Bending strengthening method and distribution of strain gages



①2ϕ18 ②CFRP stirrups ③CFRP strip ④steel plate ⑤ bolts ⑥expansion bolts ⑦ϕ6@150

Figure 7 : Shearing strengthening methods

Table 2 : Details and flexural behavior of testing beams

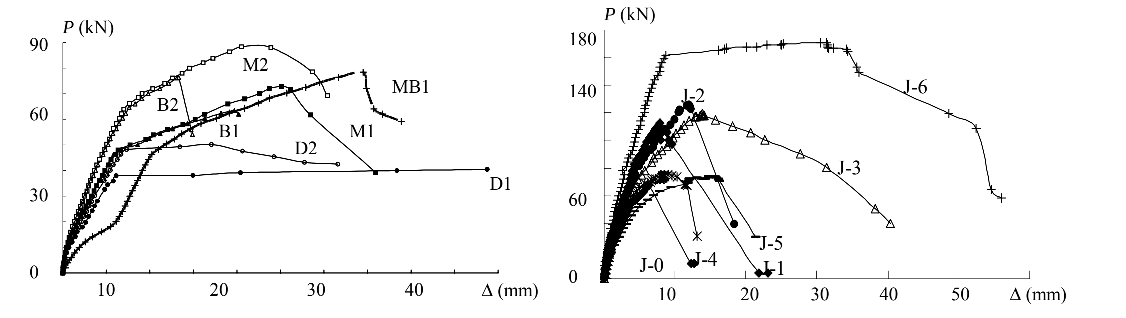
Beam	f_c (MPa)	steel bars	f_y (MPa)	A_f (mm^2)	b_f (mm)	P_i (kN)	P_y (kN)	Δ_y (mm)	P_u (kN)	Δ_u (mm)
D_1	8.9	2ɸ12	268	-	-	-	38.0	6.11	40.5	38.36
D_2	8.9	2ɸ14	305	-	-	-	46.4	6.69	50.2	17.05
D_3	7.6	2ɸ12	391	-	-	-	51.0	6.45	59.34	9.64
B_1	8.9	2ɸ12	268	25	-	-	46.4	5.83	63.3	8.59
B_2	8.9	2ɸ14	305	50	-	-	64.6	7.61	76.3	13.31
M_1	8.9	2ɸ12	268	25	100	-	46.3	6.09	72.9	25.14
M_2	8.9	2ɸ14	305	50	100	-	66.2	7.65	88.9	23.63
M_3	7.6	2ɸ12	391	17	100	-	62.8	8.62	69.8	24.83
M_4	7.6	2ɸ12	391	25	100	-	57.0	10.45	61.2	16.60
M_5	7.6	2ɸ12	391	33	100	-	63.0	6.11	111.6	36.09
M_6	6.8	2ɸ12	391	50	100	-	60.0	6.90	88.7	24.70
Y_m	4.8	2ɸ12	391	50	100	-	63.0	6.68	108.5	33.98
B_m^*	8.9	2ɸ12	268	33	200	-	44.3	9.84	78.4	34.49
H_1	4.8	2ɸ12	391	50	100	15.3	60.2	6.20	86.8	24.90
H_2	4.8	2ɸ12	391	50	100	25.5	65.8	6.70	87.3	25.43
H_3	4.8	2ɸ12	391	50	100	35.8	65.9	6.80	79.9	19.55

1. f_c = prism compressive strength of concrete, f_y = tensile strength of steel bar, A_f = section area of CFRP sheets, b_f = width of CFRP stirrups, P_i = load carried by the beam when it is strengthened, P_y = yielding load, Δ_y = yielding deflection, P_u = ultimate load, Δ_u = ultimate deflection.
2. The failure mode of B_1 is peeling off of CFRP sheets. After the test, the beam was re-strengthened. The name of the re-strengthened beam is B_m.
3. CFRP sheets (0.111mm ×150mm) were supplied by TORAY Company.
4. Epoxy was supplied by Beijing Metallurgy Building Special Materials Company.
5. Mechanical behavior of CFRP materials: Tensile strength f_f = 4286 MPa, Elastic modular E_f = 256520 MPa.

Table 3 : Details and shearing capacities of testing beams

Beam	f_{cu}/f_c (MPa)	b_f (mm)	Strengthened method	P_u (kN)	P_y/f_cbh_0
J-0	9.4/7.1	0	Fig. 7a	67.7	0.237
J-1	9.4/7.1	60	Fig. 7d	112.3	0.395
J-2	9.4/7.1	60	Fig. 7b	125.9	0.442
J-3	9.4/7.1	60	Fig. 7b	119.2	0.418
J-4	7.8/7.6	60	Fig. 7e	75.0	0.305
J-5	7.0/5.6	60	Fig. 7c	73.6	0.336
J-6	12.2/9.2	40	Fig. 7e	170.5	0.486
J-3-1	7.0/5.6	20	Fig. 7b	60.1	0.274
J-3-2	7.0/5.6	40	Fig. 7b	60.7	0.271
J-4-1	7.8/7.6	20	Fig. 7f	53.5	0.211
J-4-2	7.8/7.6	40	Fig. 7f	60.5	0.228
J-4-3	7.0/5.6	80	Fig. 7f	81.9	0.376
J-4-2-1	11.5/9.2	40	Fig. 7f	75.1	0.201
J-4-2-2	5.5/4.6	40	Fig. 7f	52.2	0.288

1. f_{cu} = cubic compressive strength of concrete, f_c = prism compressive strength of concrete, b_f = width of CFRP stirrups, P_u = shearing capacity, P_y/f_cbh_0 = ratio of shearing capacity.
2. Ratio of shear span for J-4-2-1 is 2.91, for J-4-2-2 is 1.45, for other beams is 2.18.
3. Tensile strength of steel bars is f_y = 356 Mpa; Tensile strength for CFRP sheets is f_f = 4286 MPa; Elastic modular for CFRP sheets is E_f = 256520 MPa.



(a) Load-deflection curves for flexural testing beams

(b) Load-deflection curves for shearing testing beams

Figure 8 : Load-deflection curves for some of testing beams

4 STRENGTHENING OF THE STRUCTURE

4.1 Strengthening design

Based on the experimental study results, CFRP was selected as the main strengthening material for Shanghai post office building. The typical strengthening plan for beams, slabs and columns are as shown in Figs. 9-11.

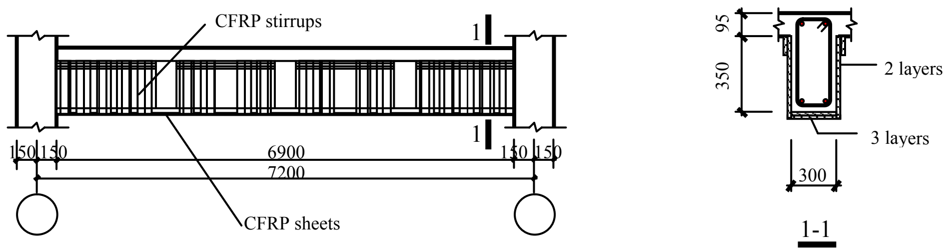
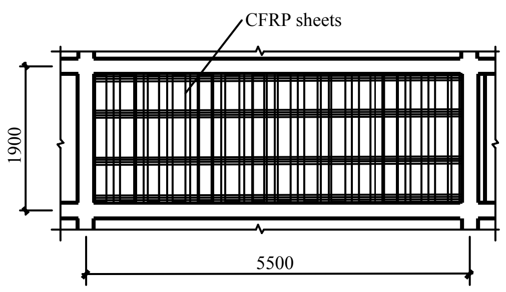


Figure 9 : Strengthening of a beam



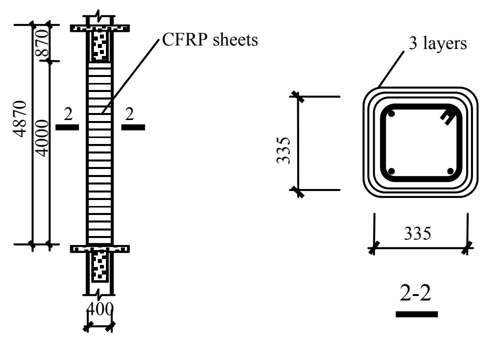


Figure 10 : Strengthening of a slab

Figure 11 : Strengthening of a column

4.2 Strengthening construction

To ensure a good and strong bond, the surface of the reinforced concrete member was prepared following a standard procedure (CECS 146, 2003).

The grinding wheel was used to prepare the surface for bonding. The coarse aggregates were exposed. The ash and debris were cleaned from the ground surface by using an air-compressor nozzle. For rectangular shape beams or columns, the sharp corners were ground into round corners with a radius greater than 20mm. Any hole or cave on the concrete surface were filled with resin mortar and ground smoothly.

After cleaning the concrete surface, saturating resin was daubed uniformly by using the roller brush. Be sure to expel all the air bubbles while taking care of the CFRP sheet. Repeat the above procedures until the last layer and daub the saturating resin uniformly.

The strengthening construction of beams, slabs and the columns are shown in Fig. 12.

The situation of the building after the construction (Fig. 1b) shows that the strengthening method for this historical building in a metropolitan city proposed by the authors is effective and applicable.

(a) Beam & slab strengthening construction

(b) Column strengthening construction

Figure 12 : Strengthening construction

5 CONCLUSIONS

To meet the retrofit requirements of the owner of the protected historical building, all of the steps including inspection, assessment, experiment study, strengthening design and construction are very important for structural engineers.

It is an effective method by gluing the CFRP sheets on the surface of the member to enhance the bending and shearing capacity of a low-strength reinforced concrete flexural member. During the construction, a proper measure is a key factor to affect the quality of the strengthening. The suitability of the strengthening method has been verified by the use of the building in half a year.

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