



Strengthening of Post-Tensioned Slab with Carbon Fiber Reinforced Polymer (CFRP)

Thammasak Rujirayanyong

Department of Civil Engineering, College of Engineering, Rangsit University, Pathum Thani, Thailand

E-mail: thammasak @rsu.ac.th

Abstract

This paper presents a case study for strengthening a post-tensioned slab using carbon fiber reinforced polymer (CFRP). Major steps that need to complete a strengthening process are analysis of a structure and then design for strengthening a structure with CFRP. However, a pull-off test for an epoxy resin by following ASTM D4541 and a load-carrying capacity test is an option that can be done to prove and make sure that the material used is acceptable and strengthened structure can resist new load conditions. For safety concerns, an existing strength of the structure should be sufficient to resist a level of this factored load ($1.1DL + 0.75LL$). If the CFRP system is damaged, the structure will still be capable of resisting a reasonable level of load without collapse. In this case study, the unstrengthen capacity of the slab without CFRP is 8,609 kg-m/m. The new design load with the factor from the analysis is 9,670 kg-m/m, and slab after strengthening with CFRP can resist bending moment at 11,483 kg-m/m while the slab displacement measured from the load test is acceptable compared with its span.

Keywords: Reinforced Concrete Structure, Strengthened Structure, Concrete Structure, Post-Tensioned Slab, CFRP

1. Introduction

The use of a building may change throughout the course of its service life, for example, its function can change, loads can increase or higher building standards become required. In some cases, old structures may need to be reinforced to extend the longevity of the structure, and most of the time it needs to be done without impacting the original design or forms especially for historical structures. Structural strengthening is a safe and secure choice. Whether the requirement is to increase the bending, shear, or seismic resistance. Carbon fiber reinforced polymers (CFRP) have been studied for strengthening structural elements (Carolin, 2003). Täljsten, Carolin, and Nordin (2003) carried out a test for concrete beams strengthened with near-surface mounted CFRP reinforcement (NSMR) compared to laminate plate bonding and the results found that several benefits can be noticed, not only higher fracture energy at failure but also better protection against fire, vandalism, and impact. Structural strengthening can be done in different ways and different materials. Glass fiber reinforced polymers (GFRP) and CFRP was studied and compared to strengthen reinforced concrete beam (Mehmet, 2014). Both materials can be used and yielded good results. Each option has pros and cons, for example, weight added to a structure, time required and original form changed but the only option that using carbon-fiber-reinforced polymer can avoid those drawbacks. CFRP is widely used for reliable and high-performance structural strengthening systems. These systems are extensively used for flexural strengthening of dynamically and statically loaded buildings and other structures such as bridges, beams, ceilings, and walls, providing outstanding long-term durability in service.

A case study in this paper is a hotel renovation project in downtown Bangkok that needs to strengthen its structure because its function changed in a certain area on the 9th floor. A new design live load is 800 kg/m² and 1,000 kg/m² that is greater than the original design. A CFRP is then used to strengthen a post-tensioned slab to sustain the new design load. A load test is required to prove that a strengthened structure can carry the load applied to the building as well as a structural epoxy resin-based adhesives can also transfer load between a CFRP and concrete properly. The two test items are required by the owner and contractor for their confidence using this strengthening method.

2. Objectives

The objectives of this paper are as followed.

- 1) To strengthen a post-tensioned slab with carbon fiber reinforced polymers (CFRP)
- 2) To do a pull-off test for an epoxy resin used in the project

[732]



3) To perform an actual load test to measure its displacement and compare with those obtained from a finite element method (FEM) analysis

3. Materials and Methods

3.1 Materials

The materials used for strengthening a slab in this study consist of CFRP fabric and structural epoxy resin-based adhesives. This renovation building was constructed for more than 30 years therefore some material properties were carefully assumed and based on as-built drawing as listed in Table 1.

Table 1 Material Properties

Concrete Strength	280	ksc
Ultimate Strength of 7-Wire PC Strand	18730	ksc
Yield Strength of 7-Wire PC Strand	16857	ksc
Diameter of 7-Wire PC Strand	12.7	mm
Yield Strength of CFRP	39000	ksc
Thickness of CFRP	0.167	mm

3.2 Methods

Some steps needed for completing the strengthening process include 1) analyzing a structure by using FEM, 2) designing for strengthening a structure with CFRP, 3) performing a pull-off test for an epoxy resin used in this project following ASTM D4541: Test Method for Pull-off Strength of coating using portable adhesion, and 4) performing a load-carrying capacity test following ACI CODE-318-11: Building Code Requirements for Structural Concrete and Commentary.

3.3 Flexural behavior of concrete section with CFRP

For strengthening concrete structures in calculating the flexural resistance of a pre-stressed section strengthened with an externally applied FRP system, there are assumptions for concrete and FRP behavior for a reinforced concrete section and addition assumptions for a pre-stressed section strengthened with an externally applied FRP system as listed in ACI 440.2R-08: Guide for the design and construction of externally bonded FRP systems. Equation (1) below can be used to calculate an area of required CFRP to strengthening a structure for any given load as shown in Figure 1.

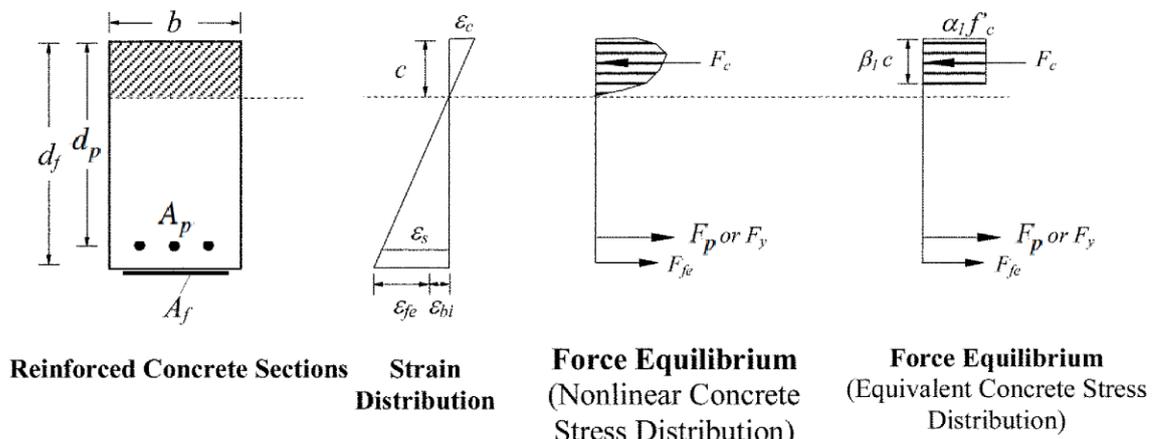


Figure 1 Flexural behavior of concrete section with CFRP

$$M_n = A_p f_{ps} \left(d_p - \frac{\beta_1 c}{2} \right) + \psi_f A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2} \right) \quad (1)$$



Whereas

M_n = Nominal flexural strength = M_u/ϕ

A_p = Area of pre-stressed reinforcement in the tension zone

A_f = Area of CFRP external reinforcement

f_{ps} = stress in pre-stressed reinforcement at nominal strength

f_{fe} = Effective Stress in the CFRP

d_p = distance from extreme compression fiber to centroid of pre-stressed reinforcement,

d_f = effective depth of FRP flexural reinforcement

c = distance from extreme compression fiber to the neutral axis

β_1 = ratio of the depth of equivalent rectangular stress block to a depth of the neutral axis

ψ_1 = FRP strength reduction factor (0.85 for flexure)

ϕ = Strength reduction factor (0.85 for flexure)

3.4 Structural Analysis with FEM

Given geometry data and load conditions as shown in Figure 2, a structural model can be created to calculate for both a bending moment to design for strengthening and deflection to compare with the one obtained from a load test.

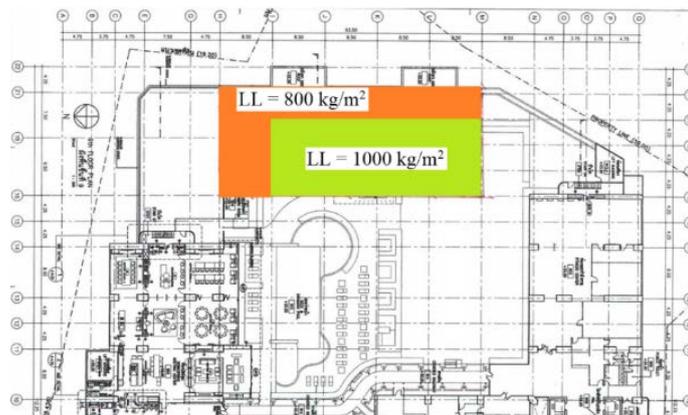


Figure 2 The area need to strengthen the structure as given a new design live load

3.5 Pull off Test

A pull-off test for an epoxy resin used in this project was following ASTM D4541: Test Method for pull-off Strength of coating using portable adhesion. There were 12 samples to be tested. It is a recommendation by ACI that bonding strength between concrete and CFRP at least 14 ksc is required to transfer force between two materials and concrete must have a strength of at least 170 ksc.

3.6 Load Carrying Test

A load-carrying capacity test is originally planned to follow ACI CODE-318-11. However, because of restriction at the site, there was an adjustment by the structural engineer to increase loading step starting from 25%, 50%, and 75% of maximum design live load respectively (250 kg/m^2 , 500 kg/m^2 , and 750 kg/m^2) by using cement bag. Structure displacement will be measured in real-time at each step until the displacement reaches a steady state, then the next loading step will start. A displacement transducer (Disp) will be mounted to the structure as shown in Figure 3.

4. Results and Discussion

4.1. Analysis Results

From the FEM analysis shown in Figures 4 and 5, bending moment can be calculated both from dead load and live load so that unstrengthen capacity without CFRP required can be checked. The existing strength of the structure should be sufficient to resist a level of this factored load ($1.1DL + 0.75LL$). If the existing structure is sufficient to resist unstrengthen capacity, then CFRP strengthening will be designed to resist ultimate capacity ($1.2DL + 1.6LL$). All results are listed in Table 3. A CFRP Detail for strengthening the structure is then prepared as displayed in Figure 6 and finally installed to the structure as shown in Figure 7.

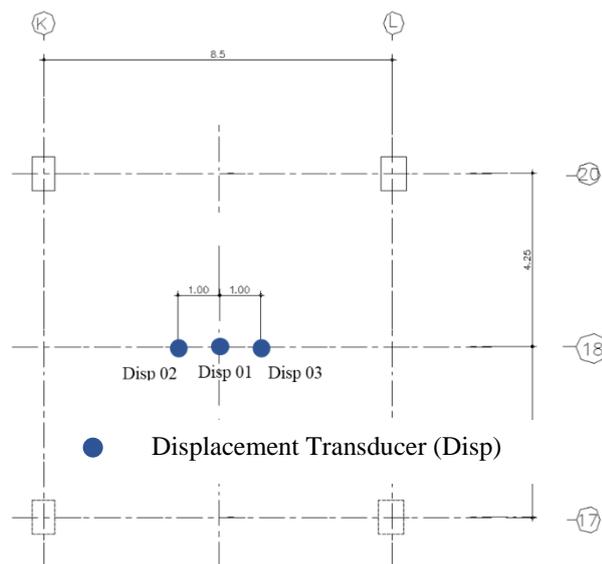


Figure 3 Location for displacement transducer and strain gage

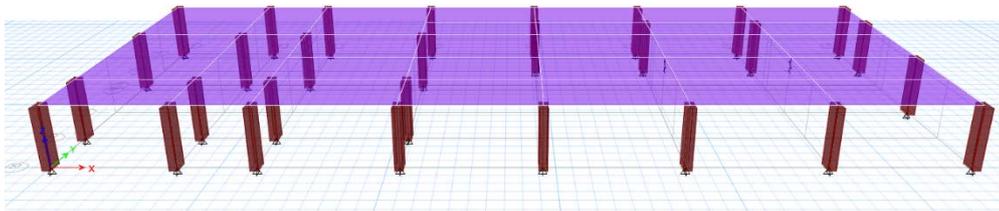


Figure 4 FEM model for analyzing the structure

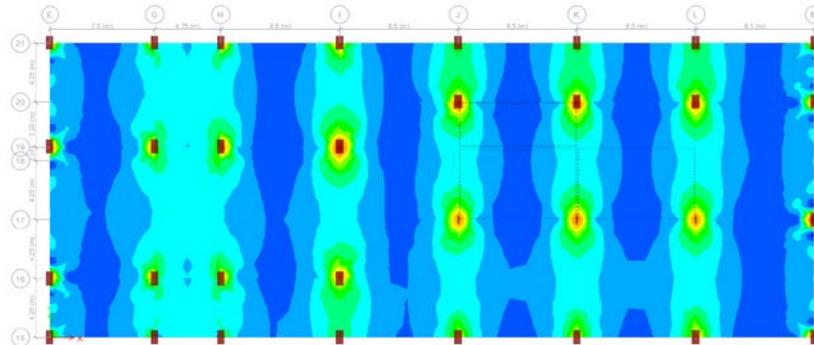


Figure 5 Maximum bending moment for design to strengthening with CFRP structure

Table 3 Capacity at each state

Unstrengthen Limit(1.1DL + 0.75LL)	5,733 kg-m/m
Unstrengthen Capacity without CFRP	8,609 kg-m/m
Ultimate Limit(1.2DL+1.6LL) (M_u)	9,670 kg-m/m
Strengthen Capacity with CFRP (M_n)	11,483 kg-m/m

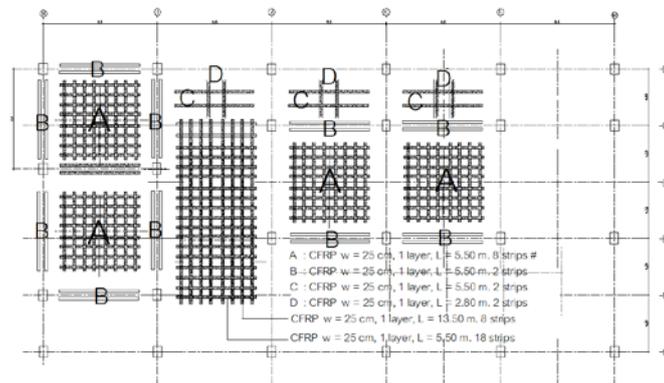


Figure 6 Detail for strengthening the structure with CFRP



Figure 7 Strengthening the structure with CFRP



4.2 Pull off Test Results

The quality of concrete repairs is determined by the adhesive strength between the repair material and the substrate. The pull-off test is the most widely used test method to assess the bonding strength. 12 samples were tested and the results are as listed in Table 4.

Table 4 Pull off Test Results

Sample No.	Bonding Strength (ksc.)	Remarks
1	56.07	Concrete Fail
2	71.36	Concrete Fail
3	30.58	Concrete Fail
4	61.16	Concrete Fail
5	71.36	Concrete Fail
6	71.36	Concrete Fail
7	40.77	Concrete Fail
8	40.77	Concrete Fail
9	71.36	Concrete Fail
10	71.36	Concrete Fail
11	61.16	Concrete Fail
12	25.48	Concrete Fail
Average	56.07	

From Table 4, the average bonding strength is 56.07 ksc, which is greater than 14 ksc as recommended by ACI. The minimum bonding strength of the lowest one is also greater than 14 ksc, while failure occurs in concrete indicated that epoxy used in the project can provide an adhesive strength needed between the repair material and the substrate.

4.3 Load Test and Displacement

During doing a load test, structural displacement will be measured in real-time at each step until the displacement reaches a steady state. An applied test is to increase the loading step starting from 25%, 50% and 75% of maximum design live load respectively (250 kg/m^2 , 500 kg/m^2 , and 750 kg/m^2) by using a cement bag. Displacement at the center of the slab is compared between analysis and real test as listed in Table 5. Figure 8 displays the displacement transducer mounted to the structure and cement bags used to load the structure. Figure 9 showed an average real-time displacement at the points according to Figure 3 at each loading step.

Table 5 Displacement Comparison

Load (kg/m^2)	Displacement at the center of the slab (mm)	
	Analyzed from FEM	Measured from the test
250	3.85	1.35
500	7.64	2.89
700	11.46	3.78



Figure 8 Displacement transducer mounted to the structure and cement bags used to load the structure.

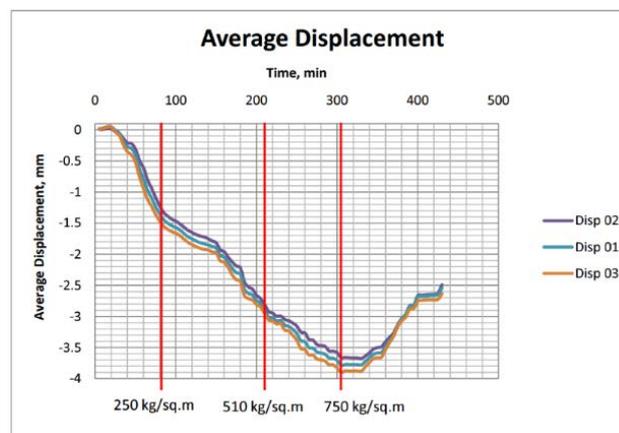


Figure 9 Average real-time displacement at each loading step

The displacement obtained from the load test is about 35 percent on average and is less than those obtained from the FEM analysis. This difference is possibly from the FEM model of the structure that might not be accurate compared with a real boundary condition of the structure. However, if compared the displacement results (3.78 mm) at 750 kg/m² with the maximum allowable displacement according to the building, the design code ($\text{span length}/480 = 17.7 \text{ mm}$) is quite small even though the condition of this load test is not both at its maximum design (1000 kg/m²) and not yet at long term condition. Based on the tested results, it can be concluded that the structure possessed a good capacity both strength and serviceability

5. Conclusion

This paper presents a case study for strengthening a concrete structure using CFRP by following ACI guidelines and installation procedures as specified by the material manufacturer. However, an adhesive strength between the repair material and the substrate is very important and has to be installed properly to make sure that the structure is strengthened as required. CFRP is gaining popularity for strengthening structure, however, owner and contractor may not yet familiar. A load test therefore sometimes is needed to prove that a strengthened structure can sustain load conditions from new required usage of a building. In this case study, unstrengthen limit is 5,733 kg-m/m while unstrengthen capacity of the slab without CFRP is 8,609 kg-m/m. The new design load with a factor from the analysis is 9,670 kg-m/m while the slab after strengthening with CFRP can resist bending moment at 11,483 kg-m/m and the slab displacement measured from the load test is very small compared with those obtained from the FEM analysis. Measured displacement from a load test, however, if compared to allowable displacement according to the design code ($\text{span length}/480$) is also quite small.



6. Acknowledgements

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7. References

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