LOAD TEST EVALUATION OF FRP-STRENGTHENED STRUCTURES

Nestore GALATI
Senior Design Engineer, STRUCTURAL TECHNOLOGIES, Maryland, USA
ngalati@structuraltec.com

Tarek ALKHRDAJI
Vice President - Engineering Services, STRUCTURAL TECHNOLOGIES, Maryland, USA
talkhrdaji@structuraltec.com

ABSTRACT: Fiber Reinforced Polymers (FRP) has recently become a mainstream technology for repair and strengthening of structures. However, for many years, the use of this FRP was relatively limited due the limited experience building officials and owners with of this technology. During these years, full scale load testing was utilized in numerous occasions to demonstrate the effectiveness of this technology and to bridge the gap between laboratory testing and full scale field installation. In-situ load testing using the Cyclic Load Test (CLT) method involves using hydraulic jacks to perform several cycles of loading and unloading that are used to obtain information on the strength and performance of a structure. Structural adequacy is then verified by examining the response of the structure to the applied loads.

Two case studies are presented in this paper that focuses on structural assessment of FRP strengthened members through load testing. In the first case study, load tests were used to confirm the performance of structural pan joist slab strengthened with externally bonded FRP in combination with a bonded concrete overlay. Load testing was also used to verify the performance floor joists strengthened for shear using FRP applied only to the sides of the joists. In the second case study, load tests were used to confirm the performance of composite structural floor system consisting of precast and cast-in-place structural elements. For all described cases, the full scale test confirmed the effectiveness of the externally bonded CFRP reinforcement and resulted in cost-effective strengthening solutions.

1. Introduction

The use of FRP for the strengthening of structures has become a mainstream practice. Many countries and professional organizations currently have a published design guide that provides the design or performance criterion, design limits, and detailing requirements. Amongst these are the documents listed in the references section of this paper (JSCE 2001, fib Bulletin 14 2001, ACI 440.2R-08 2008, S806 Canadian Standard Association 2002, Concrete Society Technical Report 55 2004, CNR-DT 200/2004).

FRP are typically used on existing structures, many of which have been in service for many years and their original structural design and constructions drawings may not be available. Determining the load carrying capacity of these structures may not be possible without detailed investigation to verify members' geometry, reinforcement details, and material strengths. Even when an investigation is carried out, many uncertainties may remain due to unknown detailing conditions or strength deterioration due to years in service. In many of these instances, load testing can be used to verify the load carrying capacity of the existing structure. Load testing can also be used to confirm is a repair or strengthening system can restore or increase the design capacity of the structures, or any of its components.

One practical load test protocol that has been successfully used to perform full scale load testing is the Cyclic Load Test Method or CLT (Galati et al., 2008, Alkhrdaji et al. 2010, ACI 437.1R-07). In this load test protocol, several cycles of loading and unloading (typically six) are used during the load test the structural elements to obtain insight into their performance and load carrying capacity. Structural adequacy is typically verified by examining the linearity of the measured deflection and the magnitude of any observed permanent deformation resulting from loading the member to near its ultimate strength.

Two case studies are presented in the following sections to demonstrate how the cyclic load testing protocol was used to validate the performance of FRP strengthened structural members and to optimize the strengthening solution to improve construction schedule and reduce the repair cost. In the first case study, load tests were used to determine the capacity of the existing floor system and to validate the performance of the structural floor after strengthening with externally bonded FRP as well bonded concrete overlay. In the second case study, the strengthening and cyclic load testing was performed on the structural floor of a large multi-story commercial building slated for increase in the design live loads due to a change in use. FRP composites were used to increase the load carrying capacity of all components of the floor system. For both case studies, externally bonded carbon FRP (CFRP) reinforcement provided a cost-effective strengthening solution.

2. Case Studies

2.1. Structural Upgrade of Commercial Floor System

This case study discusses the strengthening and cyclic load test performed on the second-level structural floor of a building located in downtown Cleveland, Ohio. The building was occupied by a department store for many years. Once became vacant, the owner of the building decided to change its use to house telecommunications equipment and become a downtown telecommunications hub, essentially a warehouse space for internet related telecommunications and other equipment. The new use of the building requires structural floors capable of supporting loads in the range of 125 psf (6.0 kPa) to 175 psf (8.4 kPa).

The building was constructed in 1917 and its structural system consists of reinforced concrete floors supported by concrete encased steel columns having height of approximately 14 ft (4270 mm), and spacing varying from 19 to 23 ft (5800 to 7000 mm). The floor system consists of reinforced concrete joists supporting a concrete slab monolithically cast with the joists.

Preliminary analysis of the existing floor system indicated that the existing beams and slab are capable of carrying the proposed loads. The existing concrete joists, on the other hand, were found deficient and their live load capacity was limited to approximately 96 psf (4.6 kPa), and was governed by the shear strength of the joists. Due to limited information on the existing structure, the exact negative and positive moment capacity of the joists could not be determined. To house telecommunication equipment, the floor needed to be upgraded to carry its own weight, a super imposed dead load of approximately 25 psf (1.2 kPa), and a service live load of 150 psf (7.2 kPa). The additional superimposed dead load was included to account for a new concrete overlay required to address the rough surface of the existing concrete slab.

The shear strength of the joists was addressed by applying FRP in the form of U-Wrap. A second option using FRP installed only on the sides of the joists (see Fig. 2) was also considered. This second option would improve the construction schedule due to reduced amount of surface preparation.

The cyclic load tests were designed to locally verify the performance of some typical joists that appeared to be the “weakest link.” To this end, the joists were loaded near their ultimate strength and their response was measured in terms of deformation and crack width. The cyclic load testing procedure involved applying concentrated loads to the test joists at predetermined locations to simulate the effect of maximum flexural forces at mid span and maximum flexural as well as maximum shear forces at the supports of the joists.

Analytical modeling of the joists indicated that the maximum moments and shear forces can be reproduced using two-point loads applied in the mid-span region, and spaced 6 ft (1830 mm) apart. The load was applied using hydraulic jacks that pulled against a reinforced concrete micro-pile that was installed on the ground floor below the second floor slab. A high strength steel bar was used to transfer the load from the jacks to the micro-pile. Linear variable differential transformers (LVDTs) were used to measure joists deflections at five locations along the span (see Fig. 1). A load cell was used to measure the applied load. All measurements were collected using a data acquisition system that allowed for real-time monitoring of the applied load and the behavior of the test joists. During the test, deflections and crack width were monitored for stability.

Two load tests were performed on the joists. Test 1 was performed on two joists that were isolated by saw-cutting the concrete slab along a line between the joists. Prior to testing, the joists were strengthened for shear using carbon FRP strengthening systems applied in the form of U-strips 12 in. (305 mm) wide and spaced at 18 in. (457 mm) on centers (see Fig. 2). The load test was terminated when the mid-span deflection became unstable and inelastic behavior was observed. Large residual deflections were measured at mid-span when the load was removed.

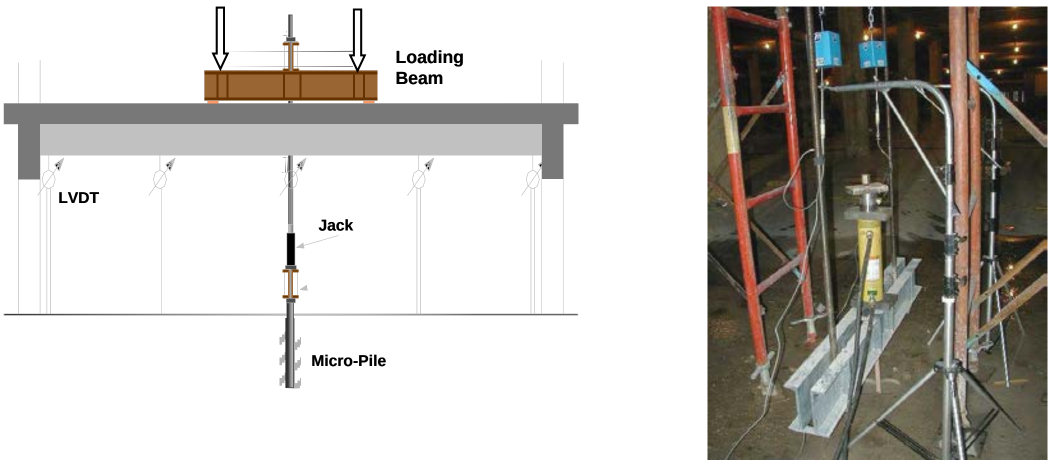


Fig. 1 – Test Setup

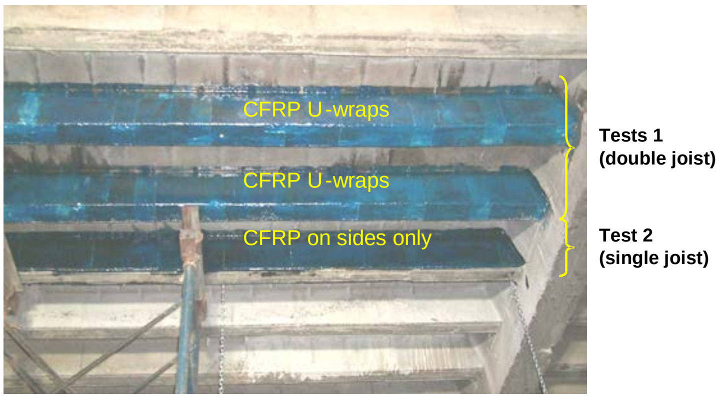


Fig. 2 – Shear Strengthening of Joists

Results of the first test indicated that failure of the joist was governed by yielding of top reinforcement at the support. No failure signs were observed at the mid-span region. Based on the test results, the joist was rated for a super-imposed dead load of 25 psf (1.2 kPa) plus a live load capacity of 135 psf (6.5 kPa). The shear performance was adequate with no shear cracks or failure signs observed.

In the second test, bonded reinforced concrete overlay was used to address the observed joist deficiency. The overlay consisted of 3 in. (76 mm) thick concrete reinforced with steel wire mesh. To ensure adequate bond between existing and new concrete, the slab surface was prepared by aggressive abrasion blasting to remove all weak concrete and provide an open-pore structure. Pull-off tests were then performed on the overlay to verify that failure will not occur at the concrete-to-concrete interface. Additionally, FRP was placed only on the sides of the joists.

Results of the second load test demonstrated the improved strength and stiffness of the joists after strengthening (see Fig. 3). Based on the test results, the strengthened joists were rated for the self-weight plus 36 psf (1.7 kPa) super-imposed dead load (RC overlay) and 150 psf (7.2 kPa) live load.

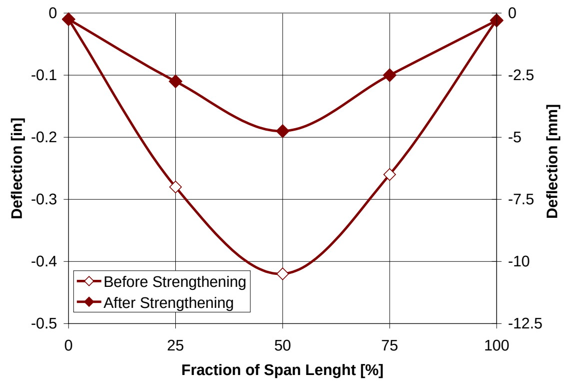


Fig. 3 – Performance of the Structure Before and After Strengthening

2.2. Case Study 2: Omni Technology Center

This case study presents how FRP strengthening was used as an economical solution to convert a major mall in South Florida to house a communications center. The structure included one million plus square foot (93,000 m^2) of slab area that consists of a one-way precast joist system simply supported on continuous composite pre-cast/cast-in-place concrete beams running normal to the direction of the joists.

The objective of the upgrade was to increase the live load capacity of the floor system from approximately 100 psf, to a new capacity including a super-imposed dead load of 25 psf (1.2 kPa) plus a uniformly distributed live load of 150 psf (7.2 kPa). Design of FRP system was achieved using ACI 440.2R-02.

The installed strengthening system consisted of multiple plies of CFRP sheets attached to joist's soffit to increase their positive bending moment capacity. CFRP strips were also wrapped around the joists' stem at each end to provide anchorage against peeling. The beams were strengthened using FRP to improve their positive and negative moment capacity. For positive moments, CFRP strips were installed on the soffit of the beam along the entire beam span. The required amount of CFRP for negative moments was equally divided and installed on each side of the column, in the direction of the beam. For shear, CFRP strips were U-wrapped around the beam for approximately 1/3 span at each end (See Fig. 4).

Due to novel use of FRP for this type of construction, the local building officials required that cyclic load tests be conducted to confirm the load rating of the existing structure and to asses the performance of the technology. The objective was to test the performance of the structural components of the floor system (slab, joist, and beam) using point loads applied at the mid-span region. To this end, 5 cyclic in-situ load tests were performed on the floor system, 3 before strengthening and 2 after FRP strengthening. The aim of the first test, TEST 1, was to verify the positive moment capacity of the existing one-way slab between the joists. TEST 2 was used to verify the positive moment capacity of the typical joist. TEST 3 was used to verify the positive moment strength of the typical beam. Two tests were conducted after strengthening: TEST 4 was conducted on FRP strengthened joists and TEST 5 was conducted on a FRP strengthened beam. Each test consisted of 6 loading-unloading cycles followed by a 24-hour test conducted in accordance to Chapter 20 of ACI 318. For all load tests, the critical test section was at the mid-span of the test member. The structural elements were loaded until the desired moment at the critical section was produced or inelastic behavior was observed.

The load test configuration was a pull-type test in which the hydraulic jack pulled against a reinforced concrete micro-pile cast into the ground on the level below (See Fig. 5). Based on the test results it was concluded that the slab had sufficient capacity to resist the new design loads. As such, no strengthening was required for the slab.

For the joists, significant residual deflections and crack widths were observed after the unstrengthened joists was unloaded. Based on the load test results of the joist, it was rated for 77 psf (3.7 kPa) dead load plus 125 psf (6 kPa) live load. FRP strengthening was then designed to provide the difference between the measured capacity and new demand.

Strengthened beam and joists

CFRP layout for negative moment strengthening

Fig. 4 – Structural Strengthening

After FRP strengthening, the joists were load tested again. Significantly smaller crack widths were measured compared to those measured prior to strengthening. No residual crack widths were measured after the load was removed. The load test confirmed that the strengthened joists are able to support its self weight plus 25 psf (1.2 kPa) super-imposed dead load and a live load of 150 psf (7.2 kPa). The load was maintained for 24 hours at the end of test cycles and was then removed. The behavior of the joist was elastic with no residual crack width (see Fig. 6).

The beam was loaded to a maximum load of 83 kip (369.3 kN). Cracking occurred at approximately 62 kip (275.9 kN). Significant residual deflections and crack width were observed after the beam was unloaded. Based on the test results and accounting for the load magnification factors and strength reduction factors of the ACI 318 building code, the tested beam did not have sufficient capacity to support the new design loads.

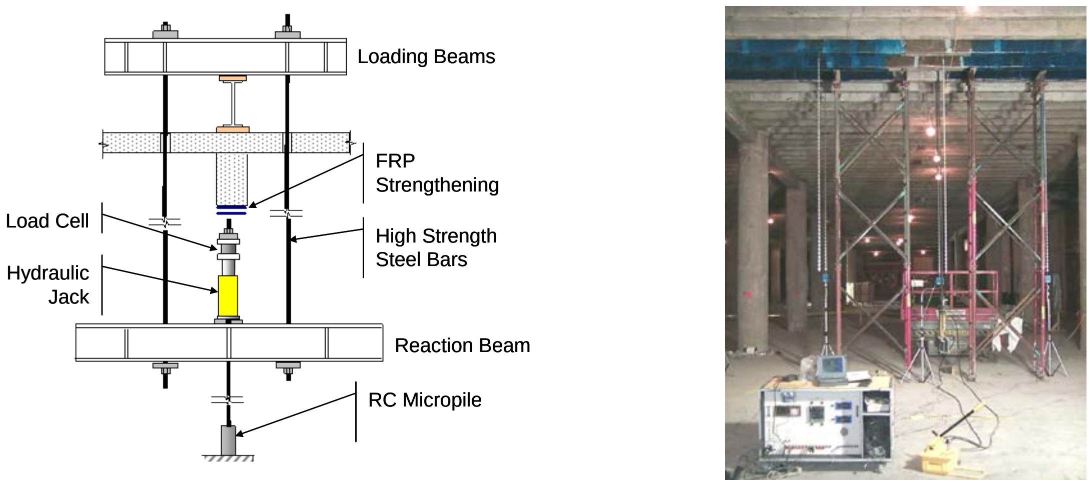
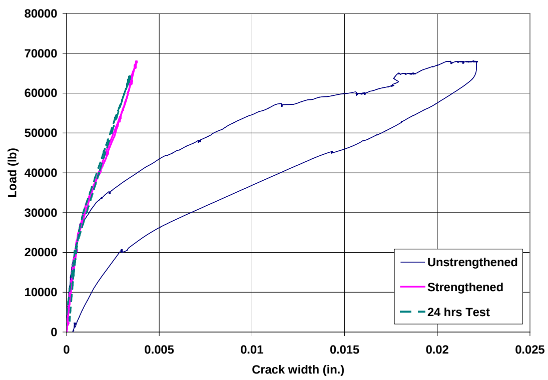
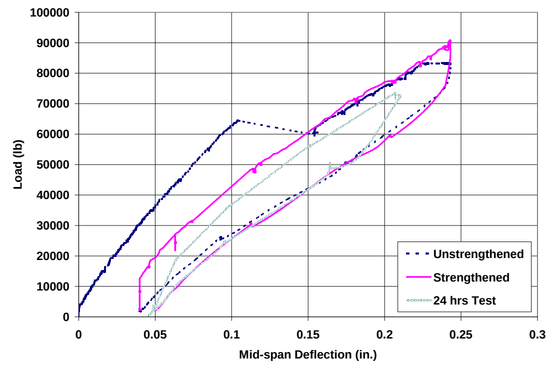


Fig. 5 – Pull-Down Test Procedure

After strengthening with FRP, the beam was again loaded to a maximum load of 91 kip (404.8 kN). Significantly smaller deflections and crack width were measured compared to those achieved prior to strengthening. Very small residual deflection was measured after the load was removed. The beam was then loaded to 73 kip (324.7 kN). This load level produced nominal positive moment at mid-span equal to 85 percent of the ultimate moment. The load was maintained for 24 hours and was then removed. The behavior of the member was almost perfectly elastic with insignificant residual deflection and crack width (see Fig. 6). Based on these results, the strengthened beam was considered adequate to support the design loads required for new use as a telecommunications center.





Measured crack width of the joist

Load-deflection curve for beam

Fig. 6 – Typical Test Results for Joist and Beam (Note: 1.0 lb = 4.4482 N; 1.0 in = 25.4 mm)

3. Conclusions

Two case studies were presented to demonstrate how the cyclic load testing protocol can be used to validate the performance of FRP strengthened structural members and to optimize the strengthening solution to improve construction schedule and reduce the repair cost.

In both of the described cases, externally bonded carbon FRP reinforcement provided a cost effective strengthening solutions. For both structures, the load test was conducted to validate the FRP technology and to reduce costs trough optimization.

4. References

ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R-08", *American Concrete Institute*, Farmington Hills, Michigan, 2008.

ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R-02", *American Concrete Institute*, Farmington Hills, Michigan, 2002.

ACI Committee 437, "Test Load Magnitude, Protocol and Acceptance Criteria (ACI 437.1R-07)," American Concrete Institute, Farmington Hills, MI, 2006, 83 pp.

Canadian Standards Association, CSA-S806, (2002), "Design and Construction of Building Components with Fibre-Reinforced Polymers," Ontario, Canada.

CNR-DT 200 (2004, 2005), "Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di Interventi di Consolidamento Statico mediante l'Utilizzo di Compositi Fibrorinforzati," Consiglio Nazionale delle Ricerche, Roma, Italy

Concrete Society, (2004), Design Guidance for Strengthening Concrete Structures Using Fibre Composite Materials, Technical Report 55, The Society, Camberley, UK.

ALKHRDAJI Tarek, GALATI Nestore, and NANNI Antonio, "Assessment of Existing Structures Using Cyclic Load Testing", Concrete International, Vol. 32, Issue 4, April 2010, pp. 39-45.

GALATI Nestore, NANNI Antonio, TUMIALAN Gustavo and ZIEHL Paul, "In-Situ Evaluation of Two Concrete Slab Systems - Part I: Load Determination and Loading Procedure," Journal of Performance of Constructed Facilities, Vol.22, No.4, August, 2008, pp. 207- 216.