REHABILITATION OF CONCRETE BRIDGES USING POST-TENSIONED CARBON FIBER PLATES

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ABSTRACT

In 2003, approximately 27% of the 590,750 bridges in the United States were considered to be structurally deficient or functionally obsolete, as determined by the Federal Highway Administration. According the American Society of Civil Engineers' (ASCE) 2005 Report Card for America's Infrastructure, bridges were given a grade of "C" (Mediocre) and it will cost $9.4 billion per year for the next 20 years to eliminate all bridge deficiencies. Since there are limited funds to build new bridges, it is often more economical to rehabilitate existing bridges while at the same time making them compliant with the current codes and loading patterns.

Different methods of rehabilitation have been used on concrete bridges over the years to strengthen and stabilize them. These include span shortening, column jacketing, steel plate bonding, deck replacement, epoxy injection and many more techniques. This paper will discuss the use of carbon fiber materials for structural strengthening, and specifically an innovative technique of post-tensioning the carbon fiber for active reinforcement. A case study will be presented, highlighting the advantages of this method in real life situations.

Keywords: Carbon fiber, Strengthening, Post-tensioned, Concrete repair, Rehabilitation, Corrosion, Bridges, Composites, Fiber reinforced polymers, External reinforcement, Tension, Chlorides, Flexural, Epoxy resin,

INTRODUCTION

In 2003, over 160,000 bridges in the United States were classified as either structurally deficient or functionally obsolete by the Federal Highway Administration. It is estimated that the cost to eliminate all bridge deficiencies is $9.4 billion per year, for 20 years (Ref. ASCE 2005 Report Card for America's Infrastructure). The Highway Bills of the past decade have not even come close to providing these types of funds to build new bridges or repair the damaged ones. However, given the current state of infrastructure and limited funding, many D.O.T.'s are choosing to "buy" additional years of life for their bridges, rather than demolish and replace, which is usually a more expensive option.

The risky approach of repair to bridges is the "patch and pray" method. More systematic approaches have proven to be effective when complete repair systems are utilized, following a thorough diagnosis and root cause analysis. When done correctly, the service life of bridges can be extended by decades, often providing enough time until funds become available for a complete replacement if warranted.

EXTERNAL POST-TENSIONING

One strengthening method that has proven effective over the years is external post-tensioning (Fig. 1). In this technique, steel rods or strands are mounted on the outside of structures and tensioned. The main purpose of external post-tensioning is to counteract the tensile stresses and deflections from externally applied loads. This technique has been used successfully in the United States for over forty years.

This method of strengthening provides active reinforcement to the structure. It can be installed either as a bonded or unbonded system, depending on the project requirements and site conditions. When installed as a bonded system, a cementitious grout is pumped around the strands in a duct, encapsulated them and providing additional protection from corrosion.

Fig. 1 External post-tensioning in parking garage

STEEL PLATE BONDING

Steel plates have been used to strengthen and stiffen concrete since the 1960's. The plates are typically bonded onto the concrete with an epoxy resin in conjunction with anchor bolts to provide shear transfer, and to temporarily hold the heavy plates while the adhesive cures (Fig. 2). This method can add tensile and/or shear strength to a reinforced concrete member, depending on its orientation and placement. Unlike external post-tensioning, this is a passive method of reinforcement, meaning the steel plates do not engage unless there is deflection in the member.

Fig. 2 Steel plate bonding on bridge beam

COMPOSITE STRENGTHENING

Composite materials have been used in the Civil Engineering marketplace since the early 1990's as a repair material. They are typically made of carbon fiber reinforced polymers (CFRP) or glass fiber reinforced polymers (GFRP). Composite materials offer the following advantages vs. conventional techniques:

- Lightweight
- Extremely high strength
- Non-corrosive
- Low installation costs
- Fabricated and sized right on site
- Little to no maintenance costs
- Adaptable to all geometries

Similar to steel plates, composites (Fig. 3) are used as supplemental reinforcement by providing passive restraint. However, their high strength:weight ratio makes them very desirable as a strengthening material, rendering steel plate bonding essentially obsolete for infrastructure repairs.

Fig. 3 CFRP Strengthening of concrete slab

POST-TENSIONING WITH CFRP

Post-tensioning with CFRP is a relatively new technique for strengthening Civil Engineering structures. This method combines the positive attributes of conventional post-tensioning with the advantages of composite strengthening. The main advantages are this method provides an active method of reinforcement, allows for optimal use of the high material properties of CFRP, reduces the tensile strain in the existing reinforcement, increases the live load capacity of the member, and is non-corrosive.

When compared to conventional post-tensioning with strands, the other advantages are:

- Light weight, allowing for easier handling
- Lower loss of prestress due to higher initial tensile strain
- Compact due to thinner section
- 406 ksi tensile strength vs. 270 ksi

When compared to conventional FRP Strengthening, the other advantages are:

- Provides active reinforcement vs. passive reinforcement
- Anchorage of ends eliminates "peeling stresses" at the ends of the plates
- Closes and maintains cracks in the tension zone of concrete
- Can be applied either as a bonded or unbonded system

SYSTEM COMPONENTS

The Sika StressHead® System is comprised of a CFRP Plate with factory mounted restraints placed at both ends (Fig. 4). A fixed anchor (Fig. 5) is attached to the concrete at the "fixed" end and a tension anchor (Fig. 6) is attached at the "live" end. If necessary, a "deviator" plate (guide plate) (Fig. 7) is fastened at mid-span to compensate for any camber. A hydraulic ram is used to apply tension to the live end, and the system is locked into place once the desired tension force is achieved.

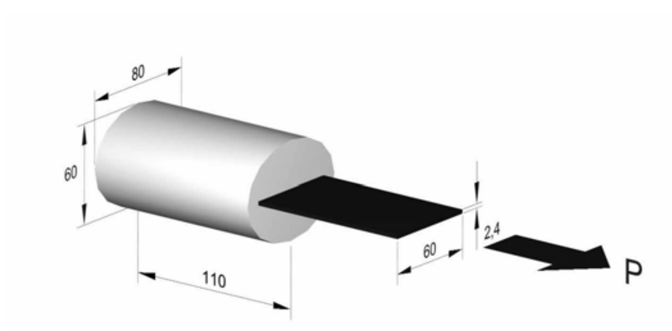


Fig. 4 CFRP Plate diagram

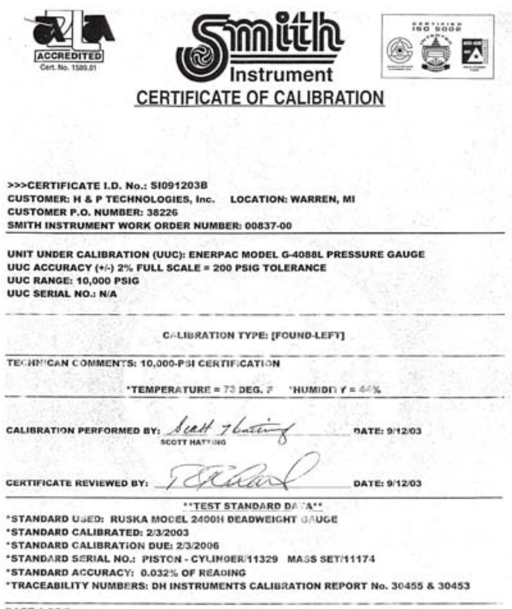
Fig. 5 Fixed end anchorage

Fig. 6 Live end anchorage

Fig. 7 Deviator plate installed mid-span

The StressHead® CFRP Plates have a design tensile strength of 2,800 MPa (406 ksi) and a tensile modulus of 165,000 MPa (23,900 ksi). The ultimate strain is 9.5 ‰. The CFRP Plates have a typical cross section of 60 mm (2.4 in.) x 2.4 mm (3/32 in.). When applying post-tensioning forces, the plates have an ultimate load capacity of 300 kN (68 kips). In practice, the tensioning is restricted to a maximum force (P_0) of 220 kN (50 kips) to prevent bursting of the concrete.

As part of the Quality Control program, all of the StressHead® plates are factory tested to P_0 + 10% prior to delivery to the jobsite. This documentation, along with the calibration records on the hydraulic jacks, is provided to the Engineer of record (see Figs. 8-9).



ACCREDITED
Cert. No. 1589.01

Smith Instrument

CERTIFICATE OF CALIBRATION

>>>CERTIFICATE I.D. No.: SI091203B
CUSTOMER: H & P TECHNOLOGIES, Inc. LOCATION: WARREN, MI
CUSTOMER P.O. NUMBER: 38226
SMITH INSTRUMENT WORK ORDER NUMBER: 00837-00

UNIT UNDER CALIBRATION (UUC): ENERPAC MODEL G-4088L PRESSURE GAUGE
UUC ACCURACY (+/-) 2% FULL SCALE = 200 PSIG TOLERANCE
UUC RANGE: 10,000 PSIG
UUC SERIAL NO.: N/A

CALIBRATION TYPE: [FOUND-LEFT]

TECHNICIAN COMMENTS: 10,000-PSI CERTIFICATION

*TEMPERATURE = 73 DEG. F *HUMIDITY = 44%

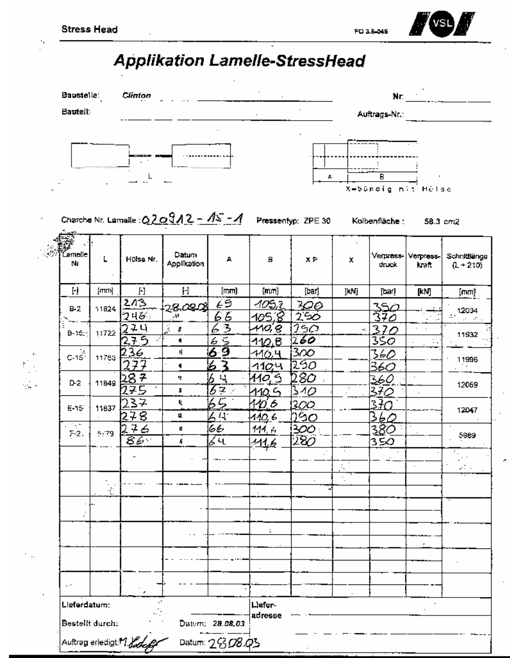
CALIBRATION PERFORMED BY: Scott Hatting DATE: 9/12/03
SCOTT HATTING

CERTIFICATE REVIEWED BY: DATE: 9/12/03

TEST STANDARD DATA
*STANDARD USED: RUSKA MODEL 2400H DEADWEIGHT GAUGE
*STANDARD CALIBRATED: 2/3/2003
*STANDARD CALIBRATION DUE: 2/3/2006
*STANDARD SERIAL NO.: PISTON - CYLINDER/11329 MASS SET/11174
*STANDARD ACCURACY: 0.032% OF READING
*TRACEABILITY NUMBERS: DH INSTRUMENTS CALIBRATION REPORT No. 30455 & 30453

PAGE 1 OF 2

Fig. 8 Example of calibration report for hydraulic ram



Stress Head FO 3.5-045

VSL

Applikation Lamelle-StressHead

Baustelle: Clinton Nr.:
Bauteil: Auftrags-Nr.:

Charche Nr. Lamelle: 020912 - 15 - 1 Pressentyp: ZPE 30 Kolbenfläche: 58.3 cm2

Lamelle Nr	L	Hülse Nr.	Datum Applikation	A	B	X P	X	Verpress-druck	Verpress-kraft	Schnittlänge (L + 210)
[-]	[mm]	[-]	[-]	[mm]	[mm]	[bar]	[kN]	[bar]	[kN]	[mm]
B-2	11824	213	28.08.03	65	105,2	300		350		12034
		246	"	66	105,8	290		370		
B-15	11722	274	"	63	110,8	290		370		11932
		275	"	65	110,8	260		350		
C-15	11786	236	"	69	110,4	300		360		11996
		277	"	63	110,4	290		360		
D-2	11849	287	"	64	110,5	280		360		12059
		275	"	67	110,5	310		370		
E-15	11837	237	"	65	110,6	200		370		12047
		278	"	64	110,6	290		360		
F-2	5779	276	"	66	111,6	300		380		5989
		86	"	64	111,6	280		350		

Lieferdatum: Liefer-adresse
Bestellt durch: Datum: 28.08.03
Auftrag erledigt: M. Schaffer Datum: 28.08.03

Fig. 9 Example of QC test

CASE STUDY: HOPKINS & CLINTON STREET BRIDGES, DEFIANCE, OH

The Hopkins and Clinton Street Bridges in the City of Defiance, Ohio were selected by the Innovative Bridge Research and Construction (IBRC) Program of the Federal Highway Administration (FHWA) for rehabilitation using advanced composite materials and structural health monitoring. The bridges have been now been strengthened and are currently being monitored for load-rating, stress and strain patterns, and deflections to determine the long-term effectiveness of the repairs.

Due to significant deterioration of the prestressed strands (Fig. 10) in the two bridges, coupled with extensive cracking and spalling of the concrete, a carbon fiber system was selected to restore the flexural strength of the beams. However, to optimize the high strength of the carbon fibers and replace the strands, of which approximately 25% were corroded, an innovative method of post-tensioning was chosen. This was the first time this post-tensioning system, known as the Sika StressHead® System, would be installed in North America, and only the sixth time it would be installed worldwide.

Fig. 10 Typical corrosion problems on Hopkins and Clinton Street Bridges

STRUCTURE CHARACTERISTICS

This project involved the structural rehabilitation of one county bridge and one state route bridge in the City of Defiance, Ohio; both bridges were part of the same contract due to their proximity to one another and similar types of damage. They were both built circa 1979 using similar construction methods.

The Hopkins Street Bridge is a six-span, two lane, precast, prestressed box beam structure with simply supported beams having a total length of 511 feet (155 m) and a width of 45 feet (14 m). The bridge, which crosses the Auglaize River, has two end spans of 79’-3” (24 m) each and two center spans of 93’-3” (28 m) each. The box beams are 36 inches (0.9m) wide and 42 inches (1.1m) deep. The deck is an asphalt wearing surface placed directly on top of the precast, prestressed box beam.

The Clinton Street Bridge is a six-span, four lane, precast, prestressed box beam structure with simply supported beams having a total length of 430 feet (131 m) and a width of 61 feet (19 m). The bridge, which crosses the Maumee River, has two end spans of 60’-6” (18 m) each and four interior spans of 76’-6” (23 m) each. The box beams are 36 inches (0.9m) wide and 33 inches (0.8m) deep. The deck is an asphalt wearing surface placed directly on top of the precast, prestressed box beams.

The box beam girder construction of these two structures is typical of DOT bridges in the United States, and many others are suffering from similar types of distress as well. All the beams have a series of solid concrete diaphragms spaced at ¼ points along their span. It was imperative that the contractor be able to precisely locate the diaphragm faces and prestressed strands using non-destructive test methods in order for the system to be installed safely and properly.

INSPECTION

The deterioration of the bridges was quite extensive, especially since the bridges were less than 25 years old. A thorough diagnosis was conducted by the Engineer to determine the root cause of the problems. Some of the factors that were considered were:

- Incorrect beam design
- Poor workmanship of the precast or the erection
- Environmental issues (chlorides, loading patterns, etc.)
- Overloading

As part of the inspection, the concrete was sounded around the areas of obvious and suspected deterioration in the tension zone of every beam. Hidden areas of distress were analyzed, especially particular crack formations in the compression zone of the bridge beams. A live-load test was conducted to measure the structures response to known loads, to measure deflections, and to locate areas that were not performing as expected.

PROBLEMS THAT PROMPTED REPAIRS

After considering all the factors, it was determined that an improperly designed drainage system was the root cause of the problem on both bridges. The original design of the structures was such that storm water drained off the bridges by flowing over the asphalt roadway through a gap between the road and a sidewalk. This drainage gap ran the entire length on each side of both bridges and was a typical deck drainage detail for these types of structures constructed in this time frame. The storm water picked up all the deleterious materials, especially de-icing salts, and deposited them onto the exposed side of the fascia box beams.

The extensive use of de-icing salts in this part of northern Ohio, over the years, allowed the chlorides a direct path to the beams, pier caps, and abutments. The corroded steel expanded in volume, causing extensive cracking, spalling and delamination of the concrete. On the Hopkins Street Bridge, there was particular damage to the roadway deck fascia beams, and on the Clinton Street Bridge, the sidewalk beams were most severely damaged.

In prestressed concrete, corrosion of the strands is a very serious issue since the steel is the primary tensile reinforcement for the beams. Also, since the strands are tensioned during construction, they are even more susceptible to failure due to stress corrosion. During inspection, it was noted that approximately 25% of the tendons were either missing or could not be counted on for strength in the affected beams. Thus, one of the objectives of the repair was to restore and reinforce the flexural capacity of the beams, as well as restore as much of the compressive force back into the beams lost by damaged tendons.

CONCRETE REPAIR

Before the bridges could be structurally strengthened, an extensive concrete repair and waterproofing program was undertaken. This involved removing all the deteriorated concrete on the superstructure down to sound, original concrete. The asphalt concrete road surface was milled down completely to the top surface of the concrete box beams. A new deck drainage system was constructed that required new stainless steel angles to be installed along the full length of the edges of the deck to prevent the drainage from spilling over the side of the fascia beams. This new system ensured that chlorides would be directed away from the concrete in the future. New stainless steel tube scuppers were installed at each end of the bridges out letting the deck drainage. A new waterproofing membrane was installed on the top surface of the concrete box beams bridge as well to prevent moisture and chlorides from penetrating in the future.

The beams were accessed using cantilevered stages, connected by 40 feet long aluminum platforms. Hardhats, safety glasses, face shields, dust masks, skin protective clothing, gloves, earplugs and handrails were utilized for safety measures.

Fig. 11 Concrete surface preparation with grinders

The areas that required the most concrete repair were the face of the abutments and the sides and the bottom of the fascia beams on each bridge. A polymer-modified bonding agent and anti-corrosion coating were used on the exposed rebar (after being cleaned) and concrete. The deteriorated areas were patched using a polymer-modified repair material containing a corrosion inhibitor for future protection. The areas patched were dictated by the project engineer after a thorough inspection was performed during construction.

ANALYSIS AND DESIGN OF REPAIRS

An in-depth inspection revealed a number of deteriorated strands for each beam. An important design assumption made by the Engineer was the amount of strength still contributed by the deteriorated strands. A number of design scenarios were set up for different conditions to meet the anticipated loads.

After calculating the deteriorated flexural strength per AASHTO guidelines and the required capacity of the beams, a beam strengthening schedule was put together. The design upgrade varied depending on the degree of damage and the moment demand for each member. The strengthening design also incorporated safety factors per ACI guidelines for environmental variables and prevention of debonding.

STRUCTURAL STRENGTHENING

A number of different carbon fiber systems were designed and installed on this project to strengthen the concrete and replace the damaged reinforcement. After repairing all the damaged concrete using conventional means, a carbon fiber wrap (SikaWrap®) was applied to stabilize the diaphragms in the anchor zones. The Plastic Sheet Method (ASTM D4263) was used to test the moisture transmission, ensuring that the repair mortar be cured and the substrate is ready to be bonded with the carbon fiber wrap. The bottom and sides of the diaphragm were mechanically grinded (ICRI CSP-3) to provide an open textured finish and the corners of the beams were rounded to a ½" radius per the specifications. A bi-directional, carbon fiber fabric (Fig. 12), impregnated with a high modulus epoxy resin, was then bonded onto the surface. After cure, the beams were ready for the next step in the strengthening process.

Fig. 12 Installation of carbon fiber fabric

The key to this project was the installation of the Sika StressHead® post-tensioned, carbon fiber plates. The post-tensioning optimized the extremely high tensile strength of the fibers (400,000 psi), reduced the crack widths in the concrete, and relieved the strain on the existing steel reinforcement in the beams under service loads while using a lightweight material that would not be susceptible to further corrosion.

The post-tensioned system was comprised of a carbon fiber plate manufactured with a factory mounted anchor at each end. One end of the plate was secured in a fixed anchorage bolted to the concrete diaphragm. The other end was placed in a moveable frame that allowed for hydraulically jacking and mechanically securing the carbon fiber plate once tensioned. Both the fixed and moveable anchorages were bolted and bonded into cored holes in the concrete, 4.5" (114 mm) in diameter and 7.5" (190 mm) deep. They ranged from 19 feet (5.8 m) to 41 feet (12.5 m) apart, depending on the beam length and diaphragm locations.

In addition to post-tensioning the plates, they were also bonded onto the concrete with an epoxy resin (Fig. 13). This provided additional stability, offered a balanced failure mode, and was also done to prevent moisture or frost from getting behind the plates over time. The carbon fiber plates were jacked in tension to forces ranging from 19,000 pounds (84 kN) to 36,000 pounds (160 kN), depending on the capacity of the diaphragms (Fig. 14). The capacity of the diaphragms was calculated via ACI using f'c determined through testing the cores taken for the anchors. This force was pre-determined by the Engineer and measured with a calibrated hydraulic ram, gauge and pump assembly. A Stressing Journal was kept by the Inspector which noted parameters such as the beam location, the location of the anchorages, the length of the plate, the displacement in the plate, the strain, and the stressing force.

Fig. 13 Epoxy resin being applied onto carbon fiber plates

Due to a slight camber in the beams, a deviator (guide plate) was used to ensure the carbon fiber plates would remain intact with the bottom of the beams after tensioning. The location of the deviator varied depending on the length and curvature of the beams. The contractor had previously surveyed the beam and noted elevations at 5 foot (1.5 m) increments to design for the camber and to calculate the exact length needed for the factory mounted plates, since the tolerance was only 2 in. (50 mm).

Fig. 14 Post-tensioning force being applied with hydraulic ram

In addition to the post-tensioned carbon fiber plates, an auxiliary, unstressed, carbon fiber strip (Sika CarboDur®) was installed on nine of the strengthened beams. This strip provided supplemental reinforcement to the beams to satisfy the flexural requirements since the diaphragms did not have the capacity to accept more than one anchorage per location or to accept the full capacity of the post-tensioned CFRP plate.

UNFORESEEN CONDITIONS

A series of laboratory tests were conducted prior to construction to verify the tensile capacity of the carbon fiber plates and the resistance of the concrete and anchorage. The stressing system is actually designed to accommodate approximately 38% higher loads than was chosen for the maximum force on this project. However, on one beam, the stressing operation caused the concrete to crack as a result of the applied load. It was determined that the substrate was inadequate to handle the force on this one beam. The decision was made to fix the concrete with additional epoxy injected into the “bubble” created in the bi-directional fabric placed in the anchor zones from the failure of the concrete in front of the anchor, rather than attempt to remove the stressed plate, since more damage would have taken place if the bonded system was removed. Consequently, the bi-directional carbon fiber fabric designed to assist the anchor zone in handling the stresses from the post-tensioned carbon fiber plates and the unknowns associated with this type of repair performed as expected ensuring that the beam’s repaired capacity was met.

CONCLUSIONS

Due to the declining state of the infrastructure in the United States, Engineers and Owners are always looking for effective means of repairing and strengthening existing structures. The use of external reinforcement has now become one more “tool in the toolbox” for contractors to install, often times adding service life onto an existing structure until additional funds become available.

The use of carbon fiber materials and other advanced composites has now become an accepted method of strengthening. Design guidelines exist in the United States (ACI 440.2R-02) and throughout the world, offering Engineers a methodology for repair based on actual testing. Post-tensioning repairs with carbon fiber plates offers distinct advantages over other methods, such as reducing the tensile strain in the existing steel reinforcement, minimizing deflections, providing a positive anchorage into the concrete, and allowing for additional service loads on structures. To date, thousands of projects have been repaired around the world with the use of composite materials, and the use of post-tensioning is just one more technique now available to Engineers.