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STRENGTHENING OF BRIDGE G270 WITH EXTERNALLY-BONDED CFRP REINFORCEMENT

by R. Mayo, A. Nanni, W. Gold, and M. Barker

Synopsis: This paper presents the results of a pilot study to apply externally bonded CFRP sheets to strengthen a simple span reinforced concrete solid slab bridge. The objective was to remove the current load posting. This bridge is a load posted structure on a heavy truck route. Strengthening with CFRP sheets was accomplished in three days without traffic interruption. Preparation consisted of light sandblasting and no concrete repair. The University of Missouri at Rolla conducted the pilot study for the Missouri Department of Transportation. The testing procedure included the construction of two test beams, to simulate bridge deck performance with and without strengthening. Laboratory setup, instrumentation and test results of two full-scale test beams are presented. Field load tests of the bridge were performed by the University of Missouri at Columbia to verify the increase in flexural strength achieved with the application of externally bonded CFRP. The method used to instrument and field load test the bridge along with the subsequence load-deflection characteristics is presented. Comparisons are made between the analytical model, laboratory beam specimens strengthened with CFRP, and in-situ field tests of the actual bridge before and after strengthening.

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INTRODUCTION

The Transportation Research Board (1) reports in the United States, there are approximately 590,000 structures in the National Bridge Inventory database. Approximately 80 percent (475,850) are classified as bridges with spans 20 feet or longer. Many of these structures have exceeded their design life and carry loads in excess of their original design. These in conjunction with fatigue and deterioration from chlorides used in anti-icing operations have left many bridges in need of repair, strengthening or replacement.

Of this number approximately 50,000 are classified as structurally deficient, 89,000 are functionally obsolete and 54,000 are both structurally deficient and functionally obsolete. This results in over 40 percent of the nations bridges needing repair or replacement. Due to budget constraints, the cost to repair or replace all of these structures is beyond the financial means of many states. Many states are forced to post load restrictions on their bridges as a stopgap measure until more funds become available for repair or replacement.

SELECTION OF BRIDGE G270

The bridge selected for demonstration of the CFRP strengthening technology is Bridge G270 located on Route 32 in Iron County. It is a 6.1 m long solid reinforced concrete slab built in 1922 with an original roadway width of 5.49 m. The bridge currently carries a traffic volume of 1600 vehicles per day. Around 1990 the original baluster handrails were removed and replaced with a thrie-beam guardrail, which expanded the roadway width to approximately 6.1 m. The bridge has a load restriction posting of 169 kN for H20 trucks and 302 kN weight limit for all others. Due to the restricted load posting and its location near a lead mine, a generator of heavy truck traffic, the Missouri Department of Transportation (MoDOT) selected this bridge for evaluation.

OBJECTIVE

The objective is to increase the load carrying capacity of bridge G270, with the application of CFRP, to allow the removal of the bridge’s restricted load posting.

Verification is to be accomplished by comparisons made between the analytical model, laboratory beam specimens strengthened with CFRP, and in-situ field tests of the actual bridge before and after strengthening.

BRIDGE RATING

General Requirements

A rating of the existing bridge live load capacity is the first step in determining the need for strengthening. The evaluation included review of the bridge construction drawings, visual inspection, and use of established state and federal guidelines (2)(3).

Until recently, MoDOT used two rating methods the Load Factor Method or the Allowable Stress Method to rate all their bridges. According to MoDOT's current load rating guidelines any structure built, rehabilitated, or reevaluated shall be rated using the load factor rating method. The current load posting on bridge G270 was developed using the allowable stress rating method.

All bridges should be rated at two load levels, the maximum load level called the Operating Rating and a lower load level called the Inventory Rating. The Operating Rating is the maximum permissible load that should be allowed on the bridge. Exceeding this level could damage the bridge. The Inventory Rating is the load level the bridge can carry on a daily basis without damaging the bridge.

In Missouri the Inventory Rating and Operating Rating, for the Allowable Stress Method, is established at the 55% and 75% stress levels respectively. The Inventory Rating and Operating Rating, for the Load Factor Method, is established at the 100% stress level.

The vehicle used for the live load calculations in both the Allowable Stress Method and the Load Factor Method is the HS20 truck or MS20 truck if a metric load rating is desired. If the above stress levels are exceeded, load posting will be required.

In Missouri, load posting is established using the H20 and 3S2 vehicles at the 68% stress level for the Allowable Stress Method or at 86% of the Operating Rating for the Load Factor Method. Additionally the Inventory Rating is calculated for the MO5, HS20 and the 4S3P vehicles. The legal load in Missouri is 205 kN for H20 vehicles and 356 kN for 3S2 vehicles.

CFRP DESIGN CALCULATIONS

Existing Bridge Condition

The rating calculations show bridge G270 requires strengthening in order to carry current traffic loads. Based on the bridge rating analysis, the new service loads will produce a maximum positive bending moment of M_s = 187 kN·m/m. The total factored loads result in a design moment of M_u = 267 kN·m/m. Material properties established by MoDOT result in a nominal concrete strength f'_c = 16.3 MPa and a yield strength for the mild steel of f_y = 207 MPa. However, these bending moments are based on "as built" plans assuming no section losses. From field observations some concrete deterioration and reinforcement corrosion has taken place along the northern edge of the soffit. From past experience bridge decks of this age with asphalt overlay experience 25–50 mm of concrete deterioration. This deteriorated concrete is located at the interface of the concrete deck and the asphalt-wearing surface. This reduction in effective depth will result in an additional 6 to 13 percent loss in moment capacity in this case.

Initial Strains

Based on existing conditions, the total dead load moment in place per unit width at the time of the CFRP installation was 74.1 kN·m. The existing strain was computed at 602 $\mu\varepsilon$ for this moment assuming the section is cracked.

PRELIMINARY DESIGN

Ultimate Strength Analysis

The ultimate limit state analysis (4) calculates the capacity of the section by combining force equilibrium, strain compatibility, and the constitutive laws of the materials at failure. The stress-strain distributions at ultimate are shown in Figure 1. The non-linear stress strain behavior of concrete may be replaced, for computational ease, by a rectangular stress block with dimensions $\alpha_1 f'_c$ x $\beta_1 c$ (5).

The general equation for the nominal moment capacity of a reinforced concrete section strengthened with CFRP flexural reinforcement is given in Equation (1).

$$M_n = A_s f_s \left(d - \frac{\beta_1 c}{2} \right) + 0.85 A_f f_f \left(h - \frac{\beta_1 c}{2} \right) \qquad (1)$$

As shown in the equation the reinforcing steel may not reach its yield stress. Strengthening with CFRP could result in over-reinforcement for moment capacity preventing the reinforcing steel from yielding. The 0.85 reduction term accounts for the novelty of the strengthening system.

The stresses in each of the materials will depend on the strain distribution and the governing failure mode. Because of the number of variables involved, there is no direct procedure for determining the strain distribution and failure mode. Instead, a trial and error procedure is necessary. This procedure involves first estimating the depth to the neutral axis and determining the failure mode based on this estimate. The estimated depth to the neutral axis may be confirmed or modified based on strain compatibility, the constitutive laws of the materials, and internal force equilibrium.

CFRP Selection

The "as built" moment capacity of the bridge is 9% below that required. In addition, compensating for the 25-50 mm loss in effective depth will require approximately a 20% total increase in moment capacity. It is reasonable that the CFRP composite strengthening system will be capable of correcting this deficiency. MBrace™ CF-130 is selected for this application with a tensile modulus of 235 GPa and a tensile ultimate strength of 3820 Mpa and a thickness of 0.165 mm.

Estimate CF-130 required

The first step is to estimate the area of CFRP based on the additional tensile force, T, required to equilibrate the moment deficiency using Equations (2) and (3).

$$T = \frac{M_u - \phi M_n}{0.90 \cdot d} \tag{2}$$

$$A_{f,est} = \frac{T}{\phi \cdot 0.85 \cdot f_{fu}} \tag{3}$$

Based on this area, the trial width of CFRP is approximately 333 mm per meter width of deck. The actual flexural capacity must now be computed by trial and error. First the depth of the concrete neutral axis was estimated at 0.15 times the effective depth. Strain levels are then computed in the CFRP, concrete and reinforcing steel. The calculated depth to the neutral axis is determined by using stresses induced by the strains. The difference in the estimated neutral axis depth and the calculated neutral axis depths are compaired. A new esitmated depth is chosen and the process continues until the difference in values is acceptable.

As a final step in the design process the serviceability stress levels in the CFRP, concrete and reinforcing steel should be checked.

Based on the analysis, one 333 mm ply of CFRP per meter width of slab will be sufficient to strengthen the bridge.

EXPERIMENTATION

Since bridge G270 was still in service applying CFRP and testing to failure was not an option. The next option was to construct a full-scale beam section that could be tested in the laboratory to failure. Copies of the original bridge plans were reviewed to determine the geometry, reinforcement layout and material properties of the bridge. The bridge plans indicated the reinforcement yield strength was 207 MPa. and the concrete was made using a 1:2:4 concrete mixture. This presented a problem since reinforcing steel with yield strength of 207 MPa. is no longer produced and the strength of a 1:2:4 concrete mixture will depend on the material characteristics used, which is unknown. Coring the existing bridge deck was not feasible due to twelve inches of wearing surface.

Due to these obstacles, a decision was made to build the test beams to mimic the existing bridge length of 16.1 m and slab depth of 470 mm. A width of 381 mm was chosen to provide an adequate surface area for the application of CFRP. Then through laboratory testing the amount of CFRP required to gain a 20% increase in flexural strength would be determined. This would be the equivalent increase in strength needed in the existing structure, using MoDOT's rating criteria, to remove the load posting.

Test Beams

Two beams were built for laboratory testing. One beam was tested to failure without strengthening for baseline comparisons. The second beam was strengthened using one ply of CFRP 304.8 millimeters wide.

Each test beam was constructed 381 mm wide, 470 mm high and 16.1 m long with the area of tension steel, As, equal to 968 mm^2. The concrete compressive strength was 39.8 MPa as determined by ASTM–C39 test procedure.

Instrumentation

The beam was instrumented with strain guages attached to the internal reinforcing steel at mid-span and on the top compression face of the beam. Deflection measurements were recorded with LVDT guages placed at the supports, quarter points and at mid-span (see Figure 2). With the predicted maximum deflection beyond the range of the LVDTs at mid-span, additional deflection measurements were recorded manually using an automatic level. A load cell was placed on top of the hydraulic jack to measure the verticle force applied.

Loading Configuration

Loading of the beam was accomplished by the use of a 267 kN hydraulic jack attached to an electric pump. The load cell on top of the jack, all LVDTs and strain gauges were attached to a data acquisition unit. The data acquisition unit continuously recorded all data while an increasing load pattern was used to load the beam. The load was increased in 22.24 kN cycles until failure occurred.

Load-Deflection Characteristics

The load deflection curves in Figure 3 show the correlation between the theoretical deflection equations and the experimental results. The theoretical deflection was determined by integrating the moment area under the theoretical moment-curvature diagram The moment-curvature diagram was calculated using concrete and steel material properties established from laboratory tests. The curves show the design methodology used is effective in determining the strength and failure modes of the reinforced concrete beams. The failure modes, as predicted, were crushing of the concrete and rupture of the CFRP respectively.

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FIELD TESTING

Application of CFRP

The bottom surface of the bridge slab had grout lines left from the original construction. These were ground smooth with hand grinders and the entire slab was lightly sand blasted to remove any loose material.

The next step was to mark the location where the CFRP was to be applied. The centerline of the slab was located and the locations of the CFRP sheets were laid out. The layout pattern consisted of eight sheets of CFRP, 508 mm wide, alternating with a 76.2 mm gap. Six sheets were used for strengthening and the two additional sheets of CFRP were added for destructive test purposes.

A two-part epoxy primer was applied to the concrete surface where the CFRP was to be applied and allowed to cure approximately twelve hours. The next step was to apply epoxy putty that served to smooth out any remaining imperfections. Immediately after the putty was applied, the first coat of epoxy saturant was applied over the entire area that was to receive one strip of CFRP.

Next a strip of CFRP was measured, cut and applied in a fashion similar to wallpaper. One end of the CFRP sheet was placed on the slab and pressed into the saturant while a second person applied the remainder of the sheet forcing it into the saturant in one continuous movement. To ensure proper embedment into the saturant and to remove any entrapped air the entire surface of the CFRP was pressed into the saturant with a small hand roller. The last step was to apply the final coat of epoxy saturant over the CFRP. The entire process was completed in three days including instrumentation and testing.

Instrumentation

The load testing equipment used to field test the elastic deflection response was provided by the University of Missouri-Columbia. The equipment consisted of a self-supporting data acquisition vehicle with the capabilities of monitoring 100 channels of strain and 25 channels of deflection. The vehicle used to load the bridge consisted of a flatbed truck loaded with steel weights. The load test vehicle, totalling 188 kN, had known axle weights of 45.4 kN. front, 72.4 kN. and 70.3 kN. for the rear axles as shown in Figure 4. The data was collected with five LVDTs placed at quarter points both longitudinally and transversely. The locations of the LVDTs are shown in Figure 5.

Load Testing

Load-deflection testing on the bridge was performed before and after the application of CFRP. Deflection tests were performed by driving the loaded truck over the bridge. The test truck made six passes over the bridge. The truck drove forward and backward on the south side, north side and centerline of the bridge. Each time the truck passed over the bridge the deflection readings were measured and recorded.

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Load Deflection Observations

Table 1 contains the tabulated results of the bridge deck deflections before and after strengthening with CFRP. The average deflection measurements after strengthening were 94% of the original. As seen from the data, deflections were not uniform. The north side of the bridge deck had some deterioration and spalling which produced the area of greatest deflections. This area, as a result of strengthening, showed the greatest reduction in the amount of live load deflection.

CONCLUDING REMARKS

This project, while small in size, demonstrates the feasibility of using externally bonded CFRP as a means to repair and rehabilitate reinforced concrete structures.

This method of strengthening is not applicable in every situation but it does provide engineers with another tool to strengthen and repair reinforced concrete structures.

Further work is needed in the areas of long term durability, fire protection and damage prevention due to vandalism.

ACKNOWLEDGEMENTS

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REFERENCES

1. Small, Edgar P., "Condition of the Nation's Highway Bridges," TR News, Transportation Research Board, No. 194, Jan-Feb 1998, pp 3-8

2. A.A.S.H.T.O. Manual for Maintenance Inspection of Bridges, American Association of State Highway and Transportation Officials, 1983, pp 19-41

3. MoDOT Bridge Load Rating Manual, Missouri Department of Transportation, Jefferson City, Missouri, 1996, pp 4.1-4.28

4. MacGregor, James C., Reinforced Concrete Mechanics and Design, 3rd ed, Prentice-Hall, Inc., 1997, pp 82-133

5. Todeschini, C., Bianchini, A, and Kesler, C., "Behavior of Concrete Columns Reinforced with High Strength Steels," ACI Journal, Proceedings, Vol. 61, No. 6, June 1964, pp 701-716

Mayo, R., Nanni, A., Gold, W. and Barker, M., "Strengthening of Bridge G270 with Externally-Bonded CFRP Reinforcement," SP-188, American Concrete Institute, Proc., 4th International Symposium on FRP for Reinforcement of Concrete Structures (FRPRCS4), Baltimore, MD, Nov. 1999, pp.429-440.

Keywords: Bridge strengthening; carbon fiber; fiber reinforced polymer; load rating; reinforced concrete

Figure captions:

Fig. 1 – Theoretical stress-strain distribution at ultimate

Fig. 2 – Test beam instrumentation

Fig. 3 – Load-Deflection curves

Fig. 4 – Test truck wheel loads

Fig. 5 – LVDT locations on bridge deck

TABLE1 – DECK DEFLECTIONS BEFORE AND AFTER STRENGTHENING

Bridge Condition	Truck Path	LVDT Deflections (mm)				
		#1	#2	#3	#4	#5
Not Strengthened	North	0.1727	0.3632	0.2210	0.1372	0.1702
	Middle	0.1778	0.2489	0.2311	0.2032	0.1753
	South	0.1499	0.1626	0.1880	0.2337	0.1473
Strengthened with FRP	North	0.1600	0.3302	0.2184	0.1295	0.1600
	Middle	0.1702	0.2184	0.2286	0.2032	0.1676
	South	0.1372	0.1245	0.1854	0.2413	0.1372
After/Before	North	0.927	0.909	0.989	0.944	0.940
	Middle	0.957	0.878	0.989	1.000	0.957
	South	0.915	0.766	0.986	1.033	0.931

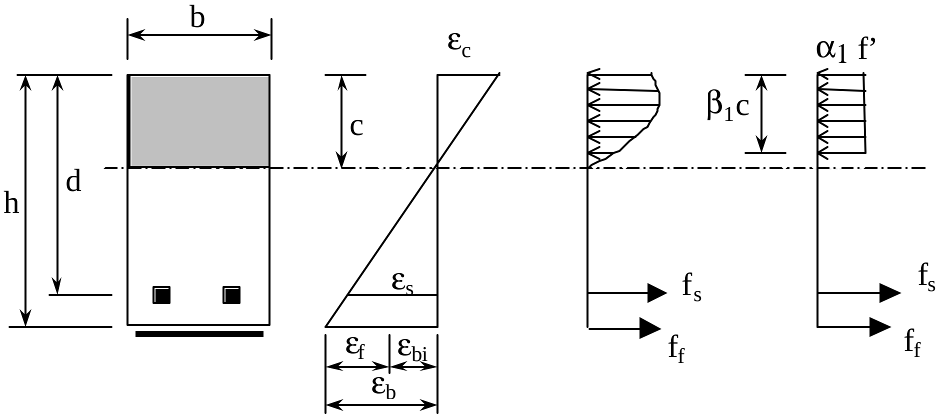

Fig. 1 – Theoretical stress-strain distribution at ultimate

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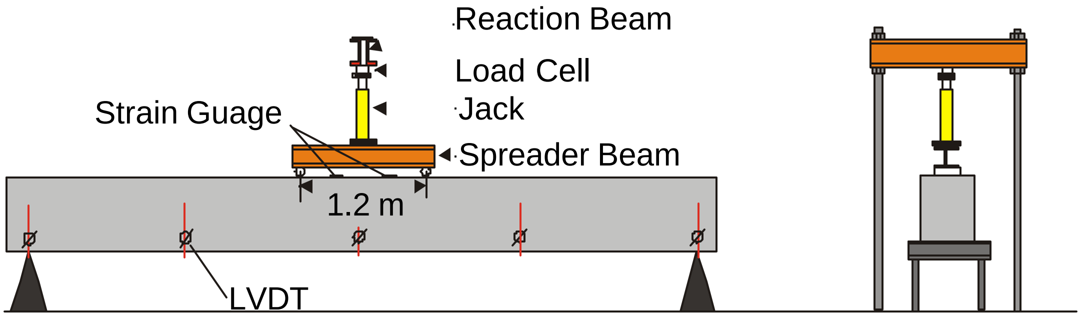

Fig. 2 – Test beam instrumentation

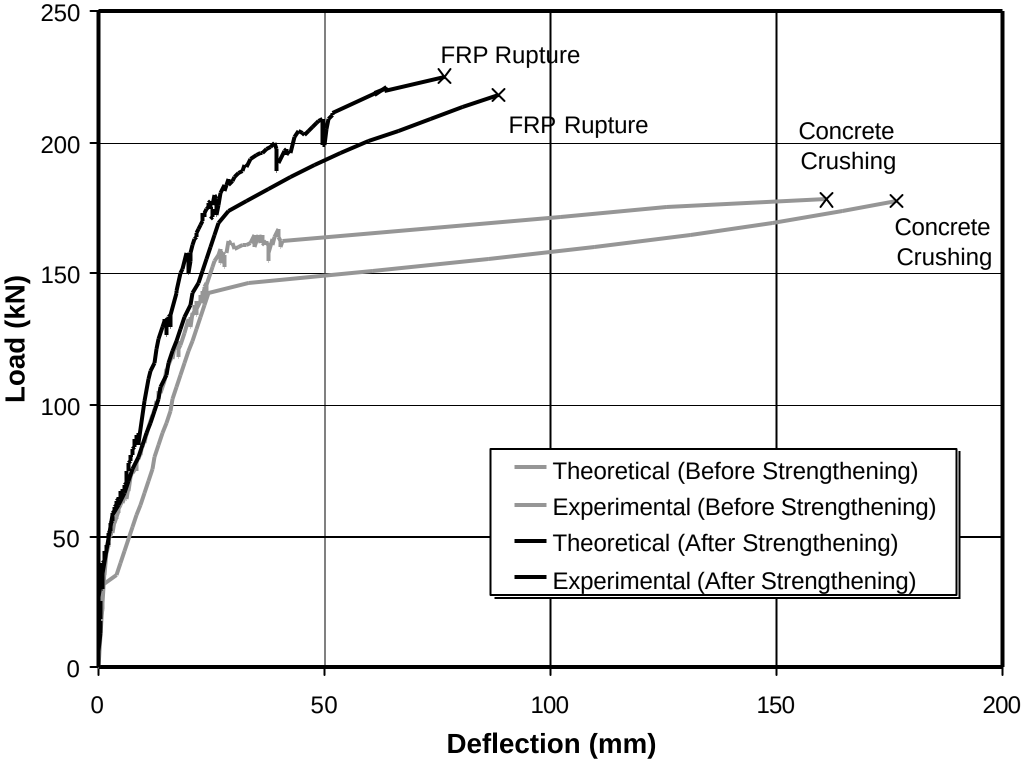

Fig. 3 – Load-Deflection curves

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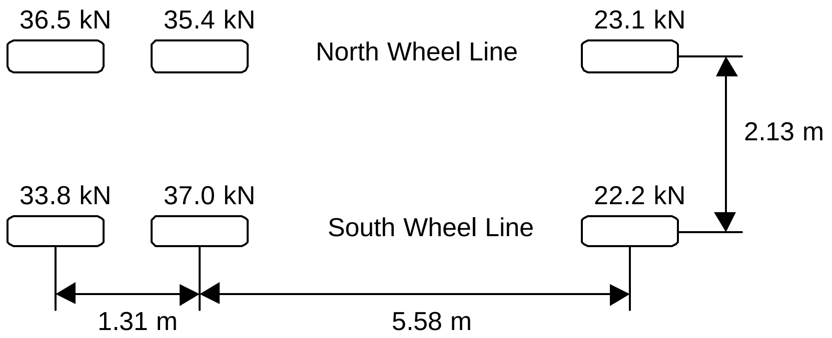

Fig. 4 – Test truck wheel loads

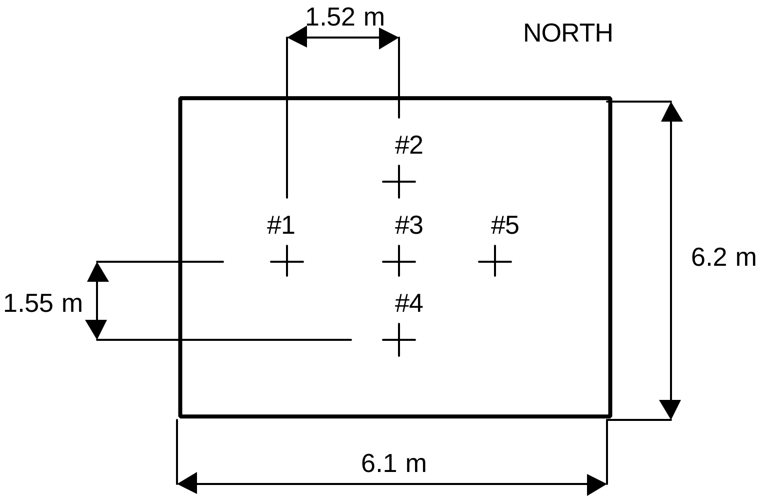

Fig. 5 – LVDT locations on bridge deck