Breakthrough

A Research Bulletin
Prepared by Organizational Results
Missouri Department of Transportation

June 2006
RI02.002

Steel-Free Hybrid Reinforced Concrete Bridge Decks Avoid Corrosion

Business Issue

By its central location, Missouri's transportation system links travelers and goods from coast-to-coast and border-to-border in the U.S. However this central location also experiences harsh winters, which is particularly hard on bridge decks. Use of nonferrous fiber-reinforced polymer (FRP) reinforcement bars (rebars) offers one promising alternative to mitigating the corrosion problem in steel reinforced concrete bridge decks. Resistance to chloride-ion driven corrosion, high tensile strength, nonconductive property and lightweight characteristics make FRP rebars attractive. However, there are design challenges in the use of FRP reinforcement for concrete including concerns about structural ductility, low stiffness, and questions about their fatigue response and long-term durability.

Background

According to the FHWA, corroded steel and steel reinforcement result in nearly 12,000 bridges being classified as structurally deficient. The direct cost of corrosion on highway bridges is estimated to be \$8.3 billion over the next ten years. This includes \$3.8 billion to replace structurally deficient bridges, \$2 billion for maintenance and cost of capital for concrete bridge decks, \$2 billion for maintenance and cost of capital for concrete substructures (minus decks), and \$500 million for maintenance painting of steel bridges. Life cycle cost analyses estimate indirect costs to the user due to traffic delays and lost productivity at more than ten times the direct cost of corrosion maintenance, repair, and rehabilitation.

Approach

New composite materials systems and design methods were investigated in a three-year collaborative research study[1] involving the University of Missouri-Columbia (UMC), University of Missouri-Rolla (UMR) and the Missouri Department of Transportation (MoDOT). The primary goal was to develop a nonferrous hybrid reinforcement system for concrete bridge decks by using continuous fiber-reinforced-polymer (FRP) rebars and discrete randomly distributed polypropylene fibers (Fig. 1). This hybrid reinforcement system comprising a combination of GFRP and CFRP continuous reinforcement with 0.5% volume fraction of 2" long discrete fibrillated polypropylene fibers, has the potential to mitigate the

Fig. 1-The hybrid GFRP/CFRP (alternate bars) reinforced full-scale bridge deck slab is ready for placement of the FRC (0.5% Vf, 2" long fibrillated polypropylene fibers) matrix.

corrosion of steel reinforcement in concrete bridge decks while providing requisite strength, stiffness, and desired ductility (often cited as concerns for FRP reinforced concrete elements). The more specific research plan included: (1) laboratory studies of static and fatigue bond performance and ductility characteristics of the hybrid reinforcement system, (2) accelerated durability tests of the hybrid reinforced specimens, (3) static and fatigue tests on full-scale conventionally reinforced and hybrid reinforced composite bridge decks (Fig. 2), and (4) development of design procedures for an FRP/FRC hybrid reinforced bridge deck.

Fig. 2-Full-scale slab being subjected to static and fatigue loads

Significant Observations and Conclusions

- Results from the experimental program showed that the incorporation of 0.5% by volume of fibrillated polypropylene fibers improved flexural ductility (Fig. 3) and flexural fatigue performance of the GFRP and CFRP reinforced specimens. The confining effect of fibers[2] greatly improves bond[3-5] and flexural fatigue performance. Fig. 3 shows the static moment –deflection response of GFRP reinforced beams with (Blue – VF8G) and without (Red – VP8G) fibers. While the polypropylene fibers do not contribute to increases in the ultimate moment capacity, they provide enhanced post-cracking and post-peak ductility. The bond performance of FRP reinforced specimens subjected to fatigue loading is also enhanced due to fiber incorporation. Smaller crack widths and more distributed cracking results in improved durability.

- Bond performance of weathered (in accelerated durability tests) specimens significantly improved due to fiber addition, which contributed greatly to improved crack growth resistance of the matrix in the vicinity of the rebar. The loss of the ultimate bond strength of the FRP rebars in the plain concrete matrix due to weathering effects was found to be 28% on average, while only 6% reduction was observed in the specimens with FRC matrix. Similarly, bond stiffness exhibited a 26% average reduction in plain concrete specimens, while only 10% reduction was observed in the FRC specimens.

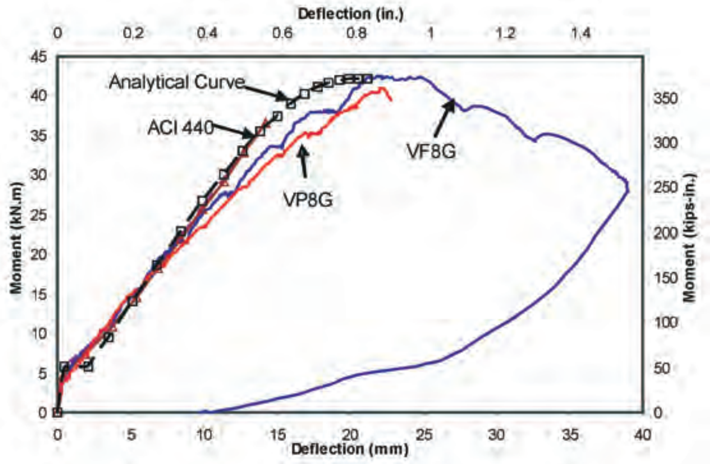

Fig. 3-Static moment-deflection response for beam reinforced with #8 GFRP reinforced bars with and without fibers.

- The pre-cracking stiffness of the three test slabs (conventional steel reinforced concrete slab, GFRP reinforced FRC slab and hybrid GFRP/CFRP reinforced FRC slab) was nearly identical because at this stage of loading the concrete matrix primarily contributes to the flexural rigidity of the slab. The post-cracking stiffness of the GFRP and hybrid GFRP/CFRP slabs were significantly lower than that for the conventional steel reinforced slab as observed from the post-fatigue static test. The overall post-cracking stiffness of the GFRP and hybrid GFRP/CFRP slabs were nearly identical, even while the modulus of the CFRP bar is higher. This was attributed to inferior bond for CFRP bars compared to GFRP bars and also to more number of finer cracks.

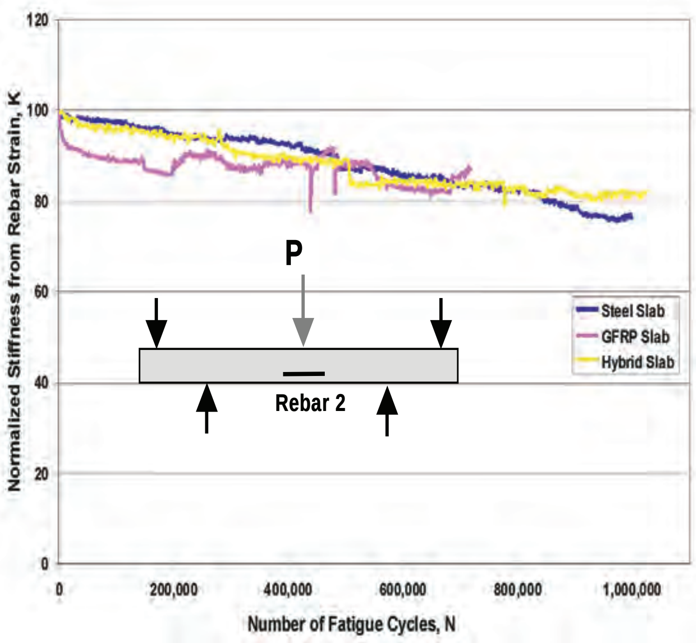

Fig. 4-Degradation of normalized stiffness due to fatigue loading for the three types of full-scale slabs tested.

- Crack widths were smaller for hybrid GFRP/CFRP slab than for GFRP slab. Crack widths for hybrid slabs were more readily comparable to that for steel reinforced slab, even while the global stiffness of the hybrid slab was more comparable to the GFRP slab. This anomaly can be explained by the presence of many finer cracks in the hybrid-reinforced slab. The two FRP reinforced slabs used 0.5% by volume of polypropylene fibers unlike the steel reinforced slab which used plain concrete matrix. Fibers affect the near surface crack widths while being insignificant as far as global properties are concerned.

- Fatigue performance under service loads of cracked elastic FRP reinforced slabs is comparable to performance of similarly loaded steel reinforced slabs during the 1 million fatigue cycles. The degradation in normalized stiffness of the FRP reinforced slabs is no different from that in conventional slabs (Fig. 4).

- Based on the results from this investigation, it is concluded that steel-free FRP reinforced bridge deck slabs can be designed to meet service performance specifications of strength normally intended for conventional steel reinforced slabs. Post-cracking deflections and associated crack widths are expected to be larger than in conventional steel-reinforced bridge deck slabs and should be recognized as such. Despite this no significant difference in fatigue performance was observed in the full-scale slab tests.

Recommendations

- The use of a hybrid reinforced concrete deck slab is recommended for field implementation. The hybrid reinforcement comprises a combination of GFRP and CFRP continuous reinforcing bars with the concrete matrix also reinforced with 0.5% volume fraction of 2-in. long fibrillated polypropylene fibers[6].

- CFRP bars are of higher modulus and strength, provide better fatigue performance and are inherently more resistant to environmental degradation. But these bars are also significantly more expensive than GFRP bars. It is hence recommended that CFRP bars be used at select locations to resist tensile cracking, limit crack widths and provide improved fatigue performance. While the slab tested in this investigation used alternate GFRP and CFRP bars in all four layers of reinforcement (longitudinal and transverse reinforcement in both the top and bottom mats), it is adequate to use CFRP bars only to resist cracking due to transverse bending in regions subjected to high tensile stresses.

- Use the working stress based flexural design procedure with mandatory check for ultimate capacity and failure mode described in Chapter 8[1]. This approach makes more phenomenological and practical sense than a design based on ultimate strength design as is currently emphasized in ACI 440[7].

MoDOT will place its first steel-free hybrid reinforced concrete bridge decks during the summer of 2007 on Boone County Route Y over Cedar Creek and Miller County Route OO over South Moreau Creek. The projects will be used to evaluate the feasibility of construction and monitor performance of the decks over time.

References

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