Epoxy-bonded glass fiber-reinforced plastic plates may provide a corrosion-free solution to increasing the load-carrying capacities of concrete bridges.

Fiber Composite Plates Can Strengthen Beams

by H. Saadatmanesh and M. R. Ehsani

About one-half of the approximately 600,000 highway bridges in the United States are in need of replacement or rehabilitation. Many of these bridges were originally designed for smaller vehicles, lighter loads, and lower traffic volumes than are common today.[1] Consequently, a large number of bridges in this country have inadequate load carrying capacities for today's traffic. Compounding this problem is the loss of strength due to corrosion of reinforcement and spalling of concrete.

These bridges must be either replaced or rehabilitated if present and future traffic needs are to be adequately served. In many cases, maintenance alone will not bring a structurally deficient bridge up to current standards — strengthening (which costs far less than replacement) must also be considered.

Among the methods used to strengthen girders in existing bridges are external post-tensioning and the addition of epoxy-bonded steel plates to the tension flange. External post-tensioning by means of high-strength strands or bars has been successfully used to increase the strength of girders in existing bridges and buildings.[2-7] This method does, however, present some practical difficulties in providing anchorage for the post-tensioning strands, maintaining the lateral stability of the girders during post-tensioning, and protecting the strands against corrosion.

The addition of epoxy-bonded steel plates to the tension face of concrete girders has been used effectively in Europe, South Africa, and Japan.[1] This method is primarily used to repair and strengthen reinforced concrete elements with insufficient load carrying capacity due to mechanical damages, functional changes, or corrosion. The principles of this strengthening technique are fairly simple: steel plates are epoxy-bonded to the tension flange of the beam, increasing both the strength and stiffness of the girder; the shear capacity of the girders can also be increased by attaching steel yokes to the web.

The advantages of this structural system include ease of application and elimination of the special anchorages needed in the post-tensioning method. A shortcoming of the method is the danger of corrosion at the epoxy-steel interface, which adversely affects the bond strength. An effective way of eliminating the corrosion problem is to replace steel plates with corrosion-resistant synthetic materials such as fiber composites. In addition to corrosion resistance, many fiber composites have tensile and fatigue strengths that exceed those of steel.

Previous studies

Much of the work in the United States has been related to the bonding of steel to steel,[8,9] while in other countries research has primarily been related to the bonding of steel to concrete.[1] Several researchers have investigated the strengthening of existing concrete girders with epoxy-bonded steel plates.[10-15]

MacDonald and Calder studied the behavior of concrete beams externally reinforced with steel plates bonded to their tension flanges.[10] They tested a series of 11.5-ft (3.5-m) and 16-ft (4.9-m) long beams in four-point bending. Each beam had a rectangular cross secton of 6 x 10 in. (150 x 250 mm). It was concluded that substantial improvements in performance could be achieved in terms of ultimate load,

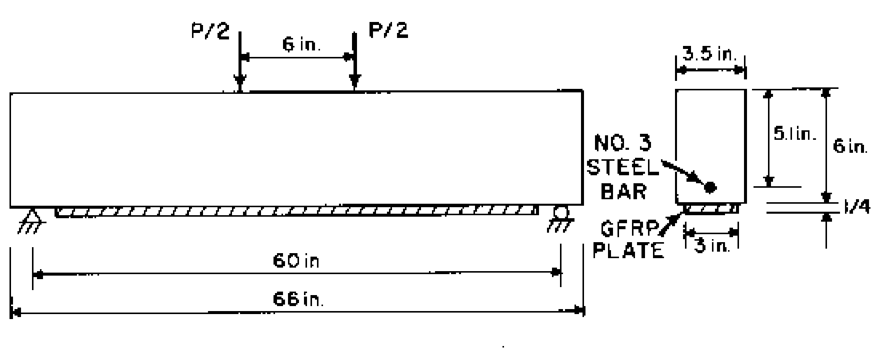

Fig. 1. — Beam test setup.

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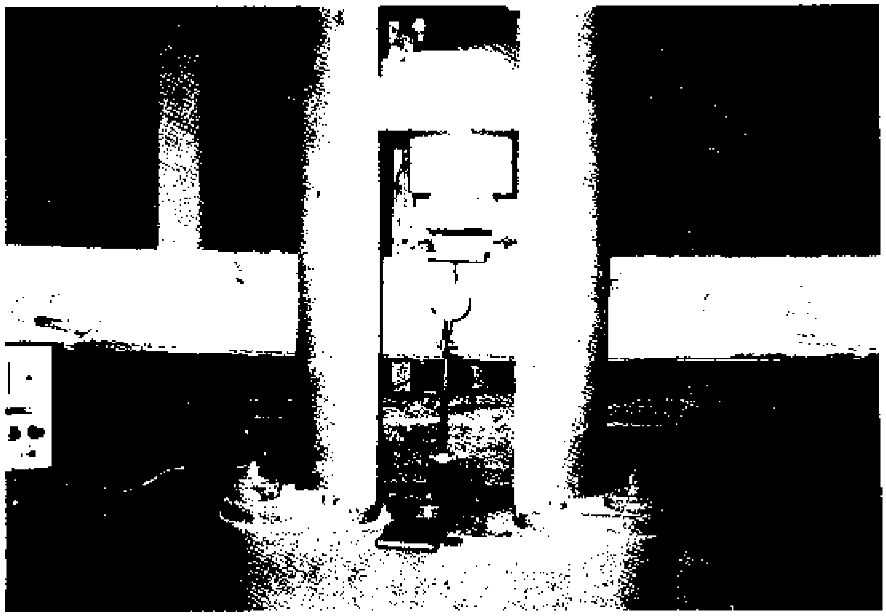

Fig. 2. — Test beam with GFRP plate attached to the tension face.

crack control, and stiffness. Exposure tests were carried out on 20 in. (0.5 m) unreinforced concrete beams with steel plates bonded to one face. Results showed that the steel plate may corrode significantly during natural exposure, causing a loss in bond strength at the steel-epoxy interface. The reduction in the overall strength of the exposed beams was attributed to corrosion.

Jones et al. reported the test results of eighteen reinforced concrete beams strengthened with steel plates bonded by epoxy glue to the tension face of the beams.[11] Two series of beams were tested. Series A beams had square cross sections of 6 x 6 in. (150 x 150 mm) and spans of 28 in. (710 mm). Series B beams had rectangular cross section of 4 x 6 in. (100 x 150 mm) and spans of 4 ft (1200 mm). Two types of glue and two types of steel plates with different yield strengths were used, and the effects of glue thickness, plate lapping, multiple plates, and precracking prior to bonding were investigated. They discussed the effects of the above variables on deflection, concrete strain distribution, cracking behavior, steel strain, mode of failure, load at first cracking, and ultimate strength, and drew the following conclusions: epoxy-bonded steel plate enlarges the range of elastic behavior, reduces the tension stresses in the concrete, delays the appearance of the first visual cracks with a resulting increase in the service loads, increases flexural strength and stiffness, and increases the ductility at flexural failure; they also concluded that a glue thickness of about 0.04 to 0.06 in. (1.0 to 1.5 mm) is the most appropriate for this type of application.

There are several field applications of epoxy-bonded steel plates to concrete girders. In the first recorded case, concrete beams in an apartment complex in Durban, South Africa, were strengthened with steel plates bonded to their tension faces, because the reinforcing steel had been accidentally omitted during construction.[16]

In the USSR in 1974, a 60-year old continuous-span reinforced concrete bridge was repaired with bonded plates.[1] Twenty-five percent of the reinforcement in the original bridge had corroded away because of poor drainage. In the negative moment region, steel plates were bonded to the clean deck surface. In the positive moment region, bolts were welded to the exposed reinforcing steel and plates were bolted and bonded to the underside of the beam. The bridge remained open to traffic while being repaired.

In Poland, where several reinforced and prestressed concrete bridges have been strengthened with adhesively bonded steel plates, this has been found to be one of the most economical and practical methods of strengthening existing bridges.[1] In one example, flat steel strips were bonded to the upper surface of the slab in the negative moment areas. In other repair works, steel plates were bonded to the underside of the concrete bridge decks.

Several bridges on an elevated highway in Japan have been strengthened with epoxy-bonded steel plates.[17] Many of the slabs in these bridges had cracked, displayed excessive spalling or scaling, or had insufficient reinforcement. Thin steel plates were bonded to the bottom of the slabs with epoxy adhesive and anchor bolts. Two construction methods were used: in one case, the adhesive was applied to the steel and concrete surfaces prior to setting; in the other, the plate was set in place first and then a liquid resin was injected in the space between the concrete slab and steel plate.

There are many other applications of epoxy bonded steel plates to concrete girders. In each case, the girder strength was significantly increased by bonding steel plates to the tension flange.

Fiber reinforced composites

Recent advancements in the fields of plastics and composites have resulted in the development of high-strength fiber-reinforced plastics (FRP's) that surpass the strength and fatigue properties of steel. These materials have been successfully used in a variety of industries such as aerospace, automotive, and shipbuilding for almost two decades. However, their use in civil engineering structures has been virtually nonexistent.

Fiber composites offer unique advantages for solving many civil engineering problems in areas where conventional materials fail to provide satisfactory service life. Unlike steel, FRP's are unaffected by electrochemical deterioration and can resist the corrosive effects of acids, alkalies, salts, and similar aggressive materials under a wide range of temperatures.[18] Fiber composites are made of small fibers bonded together with a resin matrix. The fibers provide the composite with its unique structural properties — the resin serves only as the bonding agent. The mechanical properties of composites vary with the amount and orientation of the fibers in different directions.

Glass fibers are commonly used to reinforce FRP's. The modulus of elasticity of glass fiber-reinforced plastic (GFRP) plates is relatively low (about one-fifth that of steel), therefore if structural members are built primarily out of GFRP's the resulting deflections will be five times those for steel members. However, GFRP's can perform very well for certain structural applications when combined with conventional materials, as can be seen from the results of a beam test discussed later in this article.

Other fibers such as kevlar or graphite can be used in lieu of glass to achieve significantly higher stiffness and strength in the composite product. But the cost of such composites at present is substantially higher than that of GFRP's.

Epoxy-bonded GFRP plates

In studying the behavior of beams strengthened with epoxy-bonded GFRP plates, an effort was made to limit the selection of the plates and epoxies to those which are commercially available at fairly low costs. The GFRP plates that were used in this study cost about $2.00 per pound.[15] Even though the cost per pound of GFRP plates is more than that of steel of comparable strength, due to the lower density of GFRP (one-quarter that of steel), the total cost of plates of the same size will be about the same for both steel and GFRP. Also, the corrosion resistance, light weight, and low maintenance cost of GFRP's should result in further short-term and long-term savings as compared to steel (e.g. reduced transportation costs, easier handling on construction sites, and no painting).

The success of this strengthening technique also depends on the type of epoxy used. A suitable epoxy would be one that has sufficient strength and stiffness to transfer the shear force between the plate and concrete. At the same time, the epoxy should be tough to prevent brittle failure of bond between concrete and plate. Because the behavior of steel with epoxy is different than that of GFRP with epoxy, different epoxies than those used by other researchers for bonding steel to concrete had to be used. The behavior of four different types of epoxies are discussed in this article.

Bolts can also be used in addition to the epoxy to increase redundancy and improve the shear transfer from plate to concrete. This results in additional construction cost. In this study only epoxy was used to attach the plates to the beams.

Test program

Five beams were used to test the static strength of concrete beams strengthened with epoxy-bonded GFRP plates. Four of the beams were strengthened with these plates; the fifth was not strengthened and was used as a control specimen.

Test procedure: All beams were simply-supported on a clear span of 60 in. (1525 mm) and were subjected to two concentrated loads symmetrically placed about the midspan (Fig. 1 and 2). The midspan deflection was measured using a dial gage. The strain on the surface of the composite plate was measured using two electric-resistance strain gages. The beams were incrementally loaded to failure, the same loading rate being used for all beams.

Test beams: Each beam had a cross section of 3.5 x 6 in. (90 x 150 mm) and was 66 in. (1675 mm) long. All beams were reinforced with one No. 3 Grade 60 bar (Fig. 2). The shear reinforcement consisted of 3/16-in. (5-mm) diameter wires placed at 3 in. (75 mm) spacing. The four strengthened beams had 1/4 x 6 in. (6 x 75 mm) GFRP plates epoxy-bonded to the tension flange along the full length of the beam (the only difference between these beams, designated A, B, C, and D, was the type of epoxy used). The tension face of each beam was sand-blasted down to the aggregate before the epoxy was applied.

Materials: Samples of the reinforcing steel and GFRP plate were tested under uniaxial tension. The GFRP exhibited a linear elastic behavior up to failure with a modulus of elasticity of 5,400 ksi (37.2 GPa) and an ultimate strength of 58 ksi (400 MPa) (Fig. 3). The yield strength of the shear reinforcement was 85.5 ksi (589 MPa).

Three 4 x 8 in. (100 x 200 mm) concrete cylinders were cast and tested to determine the compressive strength of the concrete. The average strength was 5,280 psi (36.4 MPa).

The four different types of two-component epoxies used in the tests were selected after consultation with a large number of manufacturers about this particular application. A tough epoxy is desirable to prevent brittle failure of the bond caused by cracking of concrete in tension. The epoxies selected had a wide range of strengths and ductilities.

Results

Beam A had the GFRP plate bonded to its tension flange using epoxy A. The uncured epoxy had a relatively low viscosity and could easily flow under a slight pressure. The cured epoxy had a rubbery texture and formed a bond line approximately 0.07 in (1.8 mm) thick. The required curing time was 24 hours at 77 F (25 C). At elevated temperature this epoxy could be cured at a much faster rate (the required curing time at 158 F [70 C] was 30 minutes). The manufacturer supplied the data on the mechanical properties of the epoxy. The tensile lap shear strength with aluminum substrates was 1900 psi (13 MPa). The maximum elongation at failure was not reported, however, this epoxy was the most flexible of all epoxies used.

The initial stiffness was slightly higher than that of the control beam (Fig. 4). The stiffness of both beams reduced after the concrete cracked at a load of approximately 1.5 kips (6.7 kN). The load-deflection curve then continued almost linearly until the longitudinal steel yielded at a load of 5.5 kips (24.5 kN). At this load large tension cracks developed, the bond between the plate and the beam failed gradually in a ductile manner, and the GFRP plate started to separate from the beam. When failure was reached, with the plate completely separating from the beam over large portions of the span (Fig. 5), there was no visible damage to either the concrete or plate surfaces. Consequently, the control beam and beam A had the same failure load.

The flexibility of epoxy A was too high to allow any measurable shear to be transferred between the plate and the beam, so no increase in the ultimate strength could be achieved. The relationship between load and strain in the composite plate is not shown because only an insignificant amount of force (3 kips [13.4 kN] maximum) was developed in the plate.

Beam B was strengthened using epoxy B. This epoxy was originally developed by the manufacturer for impact and shock resisting applications, with a maximum elongation at failure of 170 percent. The tensile lap shear strength with aluminum substrates was about 2000 psi (14 MPa), as reported by the manufacturer. The two components of the epoxy were available in spray cans and were applied sequentially to the surfaces of the beam and the plate. The epoxy was cured at room temperature for 12 hours. The cured epoxy formed a layer of about 0.04 in. (1 mm) thick at the bond line. This epoxy was tougher than the epoxy used for beam A.

The increase in the stiffness of beam B was more than that of beam A (Fig. 6). At a load of approximately 8.5 kips (37.8 kN), large shear cracks appeared in the beam and failure was imminent. The premature shear failure is attributed to the flexural strengthening of the beam without shear strengthening.

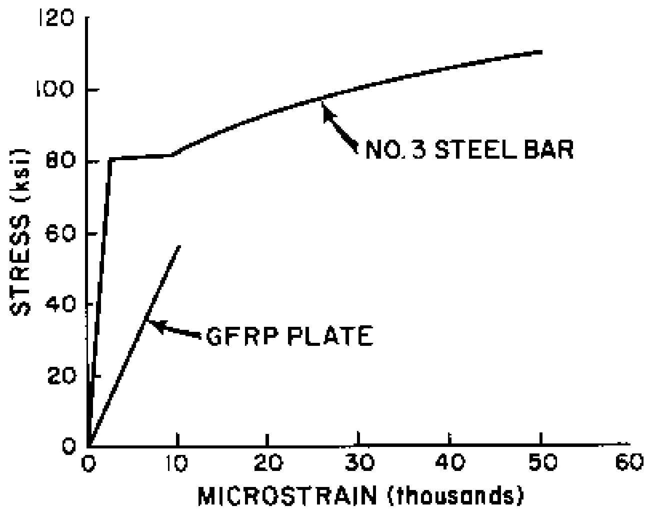

Fig. 3. — Stress-strain relationship of reinforcing steel and GFRP plate.

At this point, the beam was completely unloaded and the regions of shear distress were strengthened by means of external C-clamps. The beam was then reloaded and the loading continued until the beam failed at a load of 7.0 kips (31.2 kN). Failure was caused by the separation of the plate and the beam, particularly around the base of the large shear cracks where the bond between the plate and concrete had been severely damaged in the first cycle of loading (Fig. 7). As a result of premature shear failure, the true ultimate flexural capacity could not be reached. The maximum force developed in the composite plate was 8 kips (35.4 kN).

Beam C: was strengthened using a rubber-toughened epoxy that was relatively viscous and had a consistency similar to cement paste. The pot life of approximately ½ hour was found to be adequate for applying the epoxy to both surfaces. The bond line was approximately $\frac{1}{16}$ in (1.6 mm) thick. The manufacturer reported a tensile lap shear strength of 2000 to 2200 psi (14 to 15 MPa) for metal substrates. The maximum elongation at failure for the epoxy was 40 percent. Required curing time was 4 hours at room temperature. The manufacturer also indicated that this epoxy had a very good resistance to salt and moisture, and had originally been developed for bonding components of automobiles.

To prevent a premature shear failure similar to that observed in beam B, external shear reinforcement was provided in the end regions of beam C by means of several large C-clamps. Epoxy C performed very well, no bond failure occurring throughout the entire range of loading. In particular, there was no plateau in the load-deflection curve (Fig. 8), indicating that the increment in the tension component of the internal moment couple was carried by the GFRP plate after the reinforcing steel yielded.

Beam C was significantly stiffer than the control specimen. It was loaded to failure without any shear distress and reached an ultimate load of 13.54 kips (60 kN), more than twice that of the control specimen. The crack widths in beam C were much smaller than those in the control beam throughout the entire range of loading: there was no visible cracking up to 70 percent of the ultimate load, and thereafter the cracks were very fine and well distributed along the beam.

Failure occurred when a layer of concrete delaminated about ½ in. (13 mm) above the bond line (substrate failure) along the full beam length (Fig. 9), indicating satisfactory performance of the epoxy. This failure mode was very similar to that observed by several researchers when steel plates had been bonded to the tension face of concrete beams.[10,11]

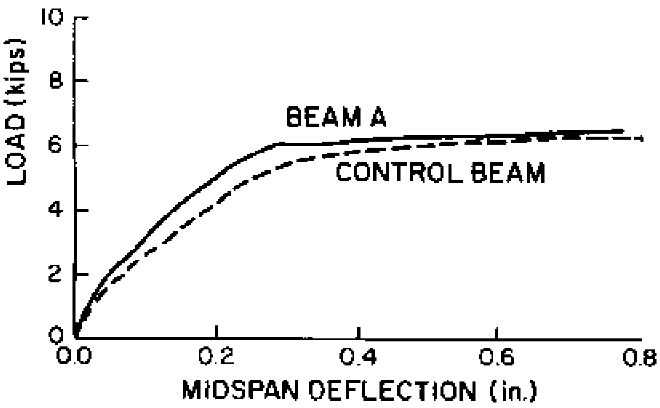

Fig. 4. — Load vs midspan deflection, beam A.

Fig. 5. — Beam A at failure

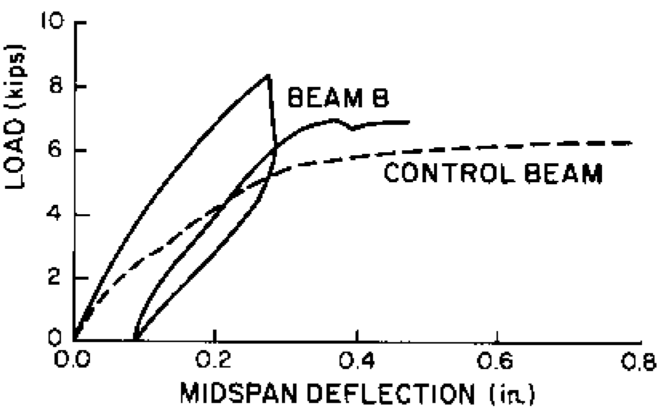

Fig. 6. — Load vs. midspan deflection, beam B.

Fig. 7. — Beam B at failure.

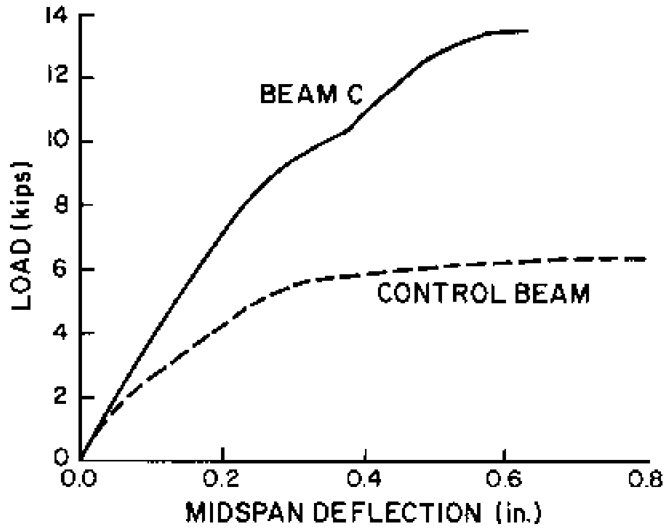

Fig. 8. — Load vs. midspan deflection, beam C.

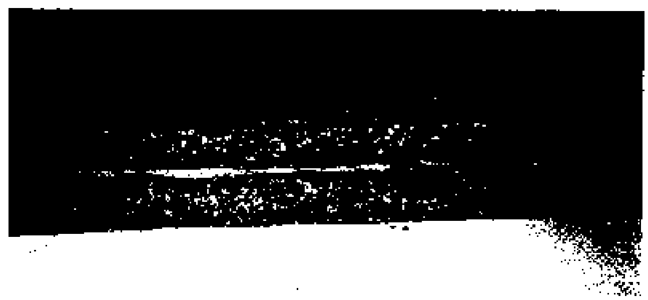

Fig. 9. — Beam C at failure.

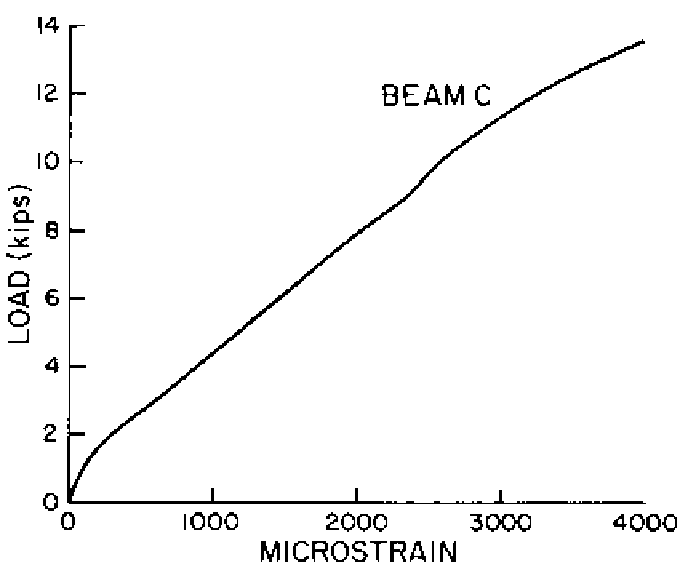

Fig. 10. — Load vs. strain in GFRP plate at midspan of beam C.

The load-strain relationship at midspan of the composite plate was bilinear (Fig 10). After the concrete cracked at a load of about 1.5 kips (6.7 kN), the tension force in the concrete transferred to the GFRP plate, resulting in higher strains. The load-strain curve continued linearly until shear failure occurred in a layer of concrete ½ in. (13 mm) above the plate. The substantial force of 21.6 kips (96 kN) developed in the GFRP plate indicates good shear transfer and composite action between the plate and concrete beam. The average shear stress in the concrete layer that failed was 266 psi (1.83 MPa) at maximum load. This was calculated by dividing the force in the plate by the plate area in the shear span.

Beam D was strengthened using the most rigid of the four epoxies tested, which had a maximum elongation at failure of only 1 percent. The consistency of the uncured epoxy was similar to the epoxy used in beam C. The overall bond line thickness was approximately 1/16 in (1.6 mm). After the concrete cracked in tension, the plate separated from the beam in a very brittle manner. The failure started near the tension cracks and immediately spread throughout the bond line. Finally, the plate completely separated from the beam with a shattering sound. The test was discontinued at this point. There was no increase in the ultimate capacity.

Ultimate strength

The ultimate strength of upgraded girders can be predicted in two ways depending on the mode of failure. If no bolts are used, (i.e., the plate is attached to the tension face with epoxy only) failure of the beam will occur either by:

- Failure of the plate (yielding of steel plate or rupture of fiber composite plate and crushing of concrete in compression)

- Shear failure of the concrete layer between the plate and longitudinal reinforcing steel, as occurred in beam C.

In the first case, and also when bolts are used to ensure complete shear transfer between the concrete and plate, the ultimate moment capacity of the beam can be calculated by the well known equations of reinforced concrete beams, and adding a moment couple consisting of the tensile force in the plate and an equal compressive force in the concrete. In the latter case, additional tests are needed to establish the limiting shear stress at which the concrete layer between the plate and the longitudinal reinforcement will fail. This stress can be related to the compressive strength f_c' of concrete.

The maximum achievable force in the plate at failure will be equal to the resultant of the limiting shear stresses. Once this force is determined, the ultimate strength of the beam can be predicted using the strain compatibility method. For design purposes, when bolts are not used, an optimum size for the plate can be calculated by equating the limiting shear force and the force in the plate. When bolts are used, they must be extended into the core region of the beam to prevent premature shear failure of concrete.

Conclusions

Strengthening concrete beams with epoxy bonded GFRP plates appears to be a feasible way of increasing the load carrying capacity of existing bridges. The flexural strength and stiffness of concrete beams can be increased by bonding GFRP plates to the tension flange using epoxy, and the behavior of beams strengthened in this way is very similar to the behavior of beams strengthened with steel plates. The use of corrosion-resistant fiber composite plates in lieu of steel is desirable because it eliminates the likelihood of bond failure as a result of corrosion of steel.

The selection of a suitable epoxy is very important in the success of this strengthening technique. In addition to improved cracking behavior, the ultimate capacity can be substantially increased when the epoxy performs well. The epoxy should have sufficient stiffness and strength to transfer the shear force between the composite plate and concrete. It should also be tough enough to prevent brittle bond failure as a result of cracking of concrete. Rubber toughened epoxies are particularly suitable for this application.

Future studies

Before this technique can be applied in the field, studies must be undertaken to address several key issues. The most important is the long-term performance of the bond at the interface of the concrete and plate, including the effects of fatigue and adverse environmental conditions. Studies should be also conducted on different types of epoxies and composite plates to select an optimum combination of the two.

Other studies may examine the percentage of longitudinal steel in beams and its effect on the selection of the area of GFRP plates. In addition, the question of increasing the shear capacity of retrofitted girders by means of GFRP plates or other techniques needs to be addressed. Some of the topics discussed above are currently under investigation at the University of Arizona.

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