

# Bridge Strengthening with Epoxy-Bonded Steel Plates

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Epoxy-bonded steel plates have been used to strengthen or repair concrete bridges in many countries around the world. Because most of the information pertaining to this subject has been published outside the United States, an extensive literature review was undertaken; this paper summarizes some of the research and applications related to this strengthening technique. Information relevant to the bonding procedure is provided, including methods for preparing the bonding surfaces and guidelines for adhesive selection and application. Research results pertaining to variations in the plate geometry, the effects of cyclic loading, and steel-to-steel bonding are also presented. Numerous applications of this strengthening technique are described. Although no original research results are presented, an extensive bibliography and a formatted table indicating the topics addressed are included for convenient reference.

Epoxy-bonded steel plates have been used to strengthen or repair bridges and buildings in many countries around the world, including South Africa, Switzerland, France, USSR, Japan, United Kingdom, Australia, Belgium, and Poland. Because this strengthening technique has not been widely researched or implemented in the United States, this paper was prepared to introduce the concept of strengthening with epoxy-bonded plates and to summarize some of the related research. In addition, a description of some applications of this procedure primarily related to bridge strengthening will be presented.

The principle of this strengthening technique is rather simple: an epoxy adhesive is used to bond steel plates to overstressed regions of reinforced-concrete members. The steel plates are typically located in the tension zone of a beam; however, plates located in the compression and shear zones have also been utilized. The adhesive provides a shear connection between the reinforced-concrete beam and the steel plate, resulting in a composite structural member. The addition of plates in the tension zone not only increases the area of tension steel, but also lowers the neutral axis, resulting in a reduction of live-load stresses in the existing reinforcement. The tension plates effectively increase the flexural stiffness, thereby reducing cracking and deflection of the member.

Epoxy-bonded steel plates have been used to repair bridges that have been damaged by accident, fire, or explosion. The technique has also been used to strengthen bridges with insufficient load-carrying capacity because of increased load requirements or a design or construction error. When applied to

bridges, this strengthening technique has several advantages. The plates can be easily handled and placed, thus allowing the procedure to be carried out relatively quickly, with minimal disruption to traffic. Also, because the plates are thin, there is almost no loss of overhead clearance. This strengthening technique is not recommended, however, for application to bridges with unsound concrete or to bridges where corrosion has been a problem unless the source of the problem is corrected.

## ASSEMBLY METHODS

Critical to the success of this strengthening technique are the selection and application of an appropriate adhesive and the preparation of the bonding surfaces (1). The steel plates must be free from oil, grease, rust, mill scale, and dirt. Oil and grease should be removed with a chemical cleaning agent. Grit blasting is the preferred method of removing dirt, scale, and rust. In research reported by Cusens and Smith (2), it was found that the shear strength of the joint improved with increased roughness of the bonding surfaces. Cleaning of the steel plates must be done shortly before bonding to avoid the development of surface corrosion or recontamination.

Preparation of the concrete surface requires the removal of all loose and unsound material. For a new concrete member, the surface laitance must be removed to expose the aggregate. Sand-blasting or grinding or both are generally used to prepare the concrete surfaces in this manner, followed by a thorough cleaning to remove all dust and debris.

There are several things to consider when an adhesive is selected for this type of application. Practical considerations to simplify the placement of the plates include the following: the temperature requirements for mixing, applying, and curing of the adhesive should be consistent with those that will exist in the field; the adhesive should also have a viscosity and pot life suitable for the particular application; and the adhesive, in most applications, should develop its strength rapidly. Long-term performance characteristics that need to be considered include the following: the shear strength of the resin should equal or exceed that of the concrete, and the adhesive should demonstrate good durability and tolerance to moisture and chemicals (1, 3).

Epoxy resin adhesives typically consist of two components: a resin and a hardener. Care must be taken when mixing the two components to ensure that the components are mixed completely and in the proper proportions. The adhesive is generally applied to both the concrete and steel bonding surfaces. The steel plate is then put in contact with the concrete surface and pressure is applied until the adhesive cures. An

alternative method involves the pressure injection of the epoxy resin between the concrete and steel surfaces. For this method, the steel plates are fastened to the concrete with bolts, using shims and spacers to maintain the desired gap between the two surfaces. After the edges of the plates have been sealed, the adhesive is pressure injected (4).

There is general agreement among the researchers that the adhesive layer should be as thin as possible while still remaining free of voids. Adhesive thicknesses ranging from 1 to 1.5 mm (0.04 to 0.06 in.) are suggested (5).

## RESEARCH

The steel plates should be designed so that the full flexural strength of the composite member can be achieved, thus ensuring ductility. Macdonald (6) reported that rapid shear failure of the concrete can be prevented with proper sizing of the bonded plates. In this study, steel plates of different widths and thicknesses but of constant cross-sectional area were epoxy-bonded to concrete beams and subjected to four-point bending tests. It was found that beams with thick, narrow plates exhibited sudden, horizontal shear failures. Thin, wide plates, on the other hand, remained bonded to the beams at the maximum sustained load, resulting in ductile failures. Macdonald suggested that an optimum width/thickness ( $b/t$ ) ratio exists at which the maximum increase in failure load and a significant increase in stiffness can be obtained while still maintaining a ductile failure. Macdonald estimated this optimum ratio to be 60.

Further research pertaining to the effects of plate geometry was reported by Swamy et al. (7). They conducted tests on a series of beams with bonded plates of constant width but varying thicknesses. Single plates with thicknesses of 1.5, 3.0, and 6 mm (0.06, 0.12, and 0.24 in.) were bonded to 155- × 255-mm (6.1- × 10.0-in.) reinforced concrete beams. In addition, beams with two layers of 1.5-mm-thick bonded plates were tested and compared with beams with a single 3-mm plate. All of the beams with plates 1.5 mm thick ( $b/t = 83.3$ ) failed in flexure with no bond distress. Beams with single plates 3.0 mm thick and two layers of plates 1.5 mm thick all exhibited a shear-bond failure; however, the shear-bond failures occurred at loads that approached the theoretical flexural strength of the beams. All of the beams with plates 6 mm thick failed by shearing of the concrete at the level of the reinforcing bars. On the basis of these results, Swamy et al. suggested two tentative design criteria: first, the  $b/t$  ratio should be no less than 50; in addition, the neutral axis depth should not be greater than 0.4 times the effective depth.

One advantage of this strengthening technique, when applied to bridges, is that the work can be accomplished with little or no interruption of traffic. The effects of cyclic loading during curing of the adhesive were examined by Swamy and Jones (8) and by Macdonald (9). Swamy and Jones found that the cyclic loading had no effect on the ultimate strength of the beams. Two different adhesives were used in the study conducted by Macdonald. The test beams with one adhesive displayed a 7 to 31 percent reduction in shear strength due to cyclic loading. No reduction in strength was recorded for the test beams with the other adhesive.

Although most of the literature pertaining to epoxy-bonded plates involves bonding steel plates to concrete beams, some research has also been reported (especially in the United States) related to bonding steel plates to steel beams. Researchers at Case Western Reserve University (10) examined the fatigue life of cover plates epoxy-bonded to the tension flanges of steel wide-flange beams. In a similar application, researchers at the University of Maryland (11, 12) combined end-bolting with the adhesive bonding of steel plates to steel beams. Both studies concluded that the use of adhesives improved the fatigue life of cover plates. The adhesive helps to distribute and transfer the load over a larger area, thus reducing stress concentrations. Findings in the study conducted by Albrecht et al. (12) indicate that adhesive bonding increased the fatigue life of cover plates by a factor of 20 over that of conventionally welded cover plates. Though Albrecht et al. advised that the method of adhesive bonding needs further research, they concluded that adhesive bonding, combined with end-bolting, has the potential of making cover plates on steel bridge girders fatigueproof.

A major problem associated with bridge strengthening using epoxy-bonded plates is the long-term durability of the connection. Ongoing exposure tests are being conducted by Calder (13). Unreinforced-concrete beams with epoxy-bonded plates were exposed to three climates, each characterized by varying levels of annual rainfall, mean temperature, and atmospheric chloride and sulfur content. Calder found that the failure load for the beams decreased rapidly during the first 8 months of exposure to approximately 60 to 80 percent of the original load. The failure loads recorded after 1 and 2 years of exposure were only slightly different from the 8-month failure loads. A significant amount of corrosion was noted at the steel-epoxy interface. The reduction in overall strength was attributed to the corrosion.

Hoigard and Longinow (14) investigated the durability of steel-to-steel bonded joints. The bonded joints were subjected to a simulated rain environment and tested after 100 and 696 hr of submersion. The author estimated that for a midwestern climate this represented 88 and 609 days of normal weathering. The specimens displayed a 9 and 12 percent loss in strength after 100 and 696 hr of submersion.

Numerous parameters related to epoxy-bonded plates have been examined by researchers. Some of these parameters are summarized in Table 1. The references, organized in chronological order, indicate the areas investigated by each of the researchers (15-31).

## APPLICATIONS

One of the first documented applications of strengthening with epoxy-bonded plates was in 1964 in Durban, South Africa, when the reinforcing steel required in a concrete beam located in a new apartment complex was accidentally omitted during construction.

In the early to mid-1970s, several buildings in Switzerland were strengthened by means of epoxy-bonded steel plates (32, 33). Reinforced-concrete floor slabs and supporting reinforced-concrete beams in a building located in Zurich were strengthened to carry additional live load. Plates were bonded to the undersides of the floor slabs and to the soffits of

TABLE 1 RESEARCH RELATED TO EPOXY BONDING

Author of Investigation	Year	Country	Reference No.	Pre-cracked Section	Reinforced & Unreinforced Sections Under & Over Reinforced Sections	Effects of Shear Reinforcement	Dimensions of Concrete Beam	Compressive Strength of Concrete	Surface Preparation of Concrete & Steel	Surface Moisture of Concrete	Type of Adhesive	Glue Thickness	Bond Length	Mechanical Fasteners	Variations in Plate Geometry or Section	Multiple Layers of Plates	Plate Lapping	Cyclic Loading During Glue Hardening	Nature of Loading (Static, Dynamic)	Rate of Loading	Fatigue Tests	Creep	Exposure to Environmental Conditions	Temperature Effects	Humidity & Moisture Effects	Use in Actual Structure	Field Tests	Moment-Curvature Relationships	Steel to Steel	Steel to Concrete
Kajfasz	1967	Poland	15																											
L'Hermite, Bresson	1971	France	16																											
Bresson	1971	France	17																											
Ladner, Flueler	1974	Switzerland	18																											
Irwin	1975	United Kingdom	19																											
Calder	1979	United Kingdom	13																											
Teoh Han	1979	Malaysia	20																											
Cusens, Smith	1980	United Kingdom	2																											
Jones, et al.	1980	United Kingdom	21																											
Raithby	1980	United Kingdom	22																											
Swamy, Jones	1980	United Kingdom	8																											
VanGemert	1980	Belgium	23																											
DeBuck, et al.	1981	Belgium	24																											
MacDonald	1981	United Kingdom	9																											
Rostasy, et al.	1981	West Germany	25																											
Jones, Swamy	1982	United Kingdom	5																											
MacDonald	1982	United Kingdom	6																											
Mays, Tilly	1982	United Kingdom	26																											
Cardon, Boulpaep	1983	Belgium	27																											
Albrecht, et al.	1984	United States	11																											
Jones, Swamy, Salman	1985	United Kingdom	28																											
Mecklenburg, ET AL	1985	United States	29																											
VanGemert, VandenBosch	1985	Belgium	30																											
Hoigard, Longinow	1986	United States	14																											
Wiener, Jirsa	1986	United States	31																											
Swamy, Jones, Bloxham	1987	United Kingdom	7																											

the beams. Shear-reinforcing plates were also bonded to the sides of the beams.

The strengthening of a reinforced-concrete tee-beam bridge in France was reported in 1972 (34). The skewed highway bridge, constructed in 1960, had developed a permanent deflection of 8 cm (3.15 in.) near the midspan of the most heavily loaded beam. The probable cause of the excessive deflection was fatigue. To strengthen the bridge, steel plates were bonded to both the sides and bottoms of the beams. At joints between adjacent plates, lap plates were bonded to provide continuous reinforcing. Up to four layers of flexural cover plates were bonded to the bottom surface of the beams.

In 1974, a highway bridge that crosses the Saint-Denis Canal in France was repaired with epoxy-bonded steel plates (35). Reinforcing plates were added to the reinforced-concrete tee-beam bridge for both flexure and shear. Traffic was maintained during preparation of the beams; however, the bridge was closed to traffic during bonding.

In the Russian city of Karastan, a continuous-span, reinforced-concrete bridge, which was constructed in 1912, was repaired with bonded plates (36). This work was completed before 1974. As a result of poor drainage, up to 25

percent of the reinforcing steel had corroded away. In negative moment regions, steel plates were bonded to the cleaned deck surface. Bolts were welded to exposed reinforcing steel in positive moment regions, and plates were then bolted and bonded to the underside of the beams. The bridge was kept open to traffic, one lane at a time, during strengthening.

By 1975, over 200 bridges on an elevated motorway in Japan had been strengthened with bonded steel plates. Thin steel plates were attached to the bottom surface of slabs by using a resin adhesive and anchor bolts (37). This strengthening technique was used on cracked slabs, slabs that displayed excessive spalling or scaling, slabs with insufficient thickness, and slabs with insufficient reinforcement. Both assembly techniques previously described (applying the adhesive directly to the bonding surfaces before setting or pressure injecting the adhesive after setting the plate) were utilized.

Also in 1975, a group of four reinforced-concrete slab bridges near Quinton, England, were strengthened with epoxy-bonded plates after cracks in the soffits were discovered (38-40). Investigations showed that inadequate tension steel had originally been provided in the cracked regions. A total of



1,376 plates, mostly 254 mm (10.0 in.) wide by 6.4 mm (0.26 in.) thick with lengths up to 3.6 m (11.8 ft), were bonded to the underside of the four bridges. In some locations, the effective thickness of the steel was increased by bonding two or three plates together. The bridges were open to normal traffic while the plates were attached and the epoxy was cured. Two additional bridges located in the United Kingdom, near Swanley, Kent, were strengthened in a similar manner in 1977. Shortly after the bridges were opened to traffic, cracks were discovered in the soffit of the beams. After it was determined that the continuous deck slabs were deficient in longitudinal steel, steel plates were epoxy bonded to the top surface as well as to the underside of the slabs.

In 1978, steel plates were epoxy bonded to the top of the concrete piers of the Shelley Bridge in Perth, Australia (41). About the time that the bridge was to be opened to traffic, shear cracks were discovered in the cantilevered portions of the piers. Plates 200 mm (7.9 in.) wide and 6 mm (0.24 in.) thick were adhesively bonded and bolted in three layers on top of each pier. Work was carried out in the winter, requiring the top of the piers to be heated to maintain a minimum temperature of 15°C (59°F) while the epoxy cured.

Two bridges over the Netekanaal in Belgium were rehabilitated in the late 1970s (24). The bridges were two of four nearly identical three-span, continuous, prestressed concrete bridges built in 1955. The rehabilitation program for the bridges included external posttensioning and epoxy-bonded steel plates. The steel plates were bonded to the undersides of the concrete stringers in the positive moment region of the center span. Additional steel plates were bonded around the webs and lower flanges of the stringers near the posttensioning anchorage beams in the end spans.

The application of adhesively bonded plates has been found to be one of the most economical and practical methods of strengthening bridges in Poland (42). Adhesively bonded plates have been used to strengthen several reinforced-concrete and prestressed-concrete bridges. In one example, flat steel strips were bonded to the upper surface of the slab bridge in the negative moment areas. Other repair work has included the bonding of flat strips to the lower surface of the concrete bridge deck, in which the strips were fastened at the ends with bolts or bonded and anchored with bolts to the side surfaces of concrete slabs.

## SUMMARY

Epoxy-bonded steel plates can effectively be used to increase the live-load capacity of a concrete bridge. By adding tension reinforcement, the neutral axis of a member is lowered and the stresses in the existing reinforcement are reduced. The strengthened member acquires increased flexural stiffness, resulting in a reduction in cracking and deflection. The procedure requires careful preparation of the bonding surfaces and proper mixing and application of a suitable epoxy adhesive. The steel plates should be designed so that failure, if it occurs, is a ductile failure instead of a sudden, shear-bond failure. To meet this requirement, researchers suggest that the  $b/t$  ratio of the plate be no less than 50.

Although this strengthening technique has primarily been applied to concrete members, research related to bonding steel

plates to steel members has also been undertaken. The fatigue life of bonded steel cover plates increased by a factor of 20 over that of conventionally welded cover plates.

An area needing more research is the long-term durability of the bonded connection. Significant corrosion and loss in strength have been noted in both steel-to-concrete and steel-to-steel bonded connections after they were subjected to exposure tests. Until this problem is resolved, this strengthening procedure is not recommended as a permanent solution.

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