

Use of Epoxy Compounds as a Shear Connector in Composite T-Beams

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•APPROXIMATELY twenty years ago, epoxy resin compounds were introduced in this country. Since that time new developments and improvements of the compounds have been made, and practical applications in the highway field have been established. With the exception of the aircraft industry, the one area which has remained largely unaffected by these compounds is that of structural connections for the building and highway construction industries. The work of the aircraft industry in bonding plastic or metal cores to metallic skins for forming sandwich panels (1) and the reports of high tensile and shear strengths both in bond and in material have suggested that further practical applications of the epoxy compounds as a structural connector are warranted. One of the first such possible uses in the highway field subject to investigation was the use of epoxy resin compounds as a shear connector for composite T-beams.

The New York State Department of Public Works reports (2) that the first research conducted for the specific use of epoxy resin compounds as a shear connector was carried on in the laboratories of the Sika Chemical Corporation, Passaic, N.J. The Civil Engineering Department of the University of Arizona began similar investigations in 1959, and on July 1, 1960, they continued research under a formal contract with the Arizona Highway Department and the U.S. Bureau of Public Roads. Similar efforts were proposed by the senior bridge engineer of the California Division of Highways in 1961 (3), and in October 1962 the Civil Engineering Department of Rensselaer Polytechnic Institute, under contract to the Bureau of Physical Research, Department of Public Works, State of New York, reported the first half of its investigations (4).

ADVANTAGES OF EPOXY SHEAR CONNECTOR

Three highway departments, two at opposite boundaries of the continental United States, independently gave consideration to this proposed use of epoxy resin compounds and considered such studies worthy of support. This consideration was, and still is, supported by the U.S. Bureau of Public Roads. The possible benefits to be gained by this type of construction include the following.

1. Reduction of Bridge Deck Cracking. —The deterioration of bridge deck slabs, where mechanical connectors have been used, may be explained in part by the presence of high thermal and shrinkage stresses (this point has been subjected to much controversy among authorities). These stresses, when combined with vibration and impact stresses, may cause excessive strains and stresses resulting in cracking which may later lead to the spalling of the bridge deck. In support of this theory it is reported that visible shrinkage cracks did not develop in the slabs of epoxy-glued T-beams,

whereas similar mechanically connected T-beams developed large visible shrinkage cracks (5). This difference apparently existed because the epoxy compound was able to adjust during its setting process to the shrinkage of the concrete during its curing process. Likewise, the elastic properties and low modulus of elasticity of the epoxy compound probably alleviate thermal stresses to a great degree by providing a membrane which can adjust between the slab and stem later while the beam is in service.

2. Provision of a Continuous Connector.—Mechanical connectors, by the very nature of the function provided, develop stress concentrations in the bridge decks along the points of contact. An epoxy compound used in this manner provides a continuous connection between the deck and beam or girder, eliminating stress concentrations and resulting in more integral beam action.

3. Elimination of Construction Hazards.—Mechanical connectors, which the epoxy compounds would replace, are generally applied to the beams or stringers before the deck form work has begun. Hence, workmen must continually face the hazard of tripping over the connectors and falling. Some safety and ease of construction would be achieved by removing these connectors from the working surfaces.

4. Economy.—One of the most important and most common questions arising from the topic of an epoxy shear connector is that concerning the economy of its use. Aside from the economic factors previously discussed, and considering that successful application and use can be made with an epoxy compound, it is unlikely that any significant differences in initial construction costs would exist between the two joinery methods. Because deck cracking is presumably a major cause of deck deterioration, sometimes requiring deck replacement within a few years, this system may provide a major economic advantage. Costs of deck replacement on a typical bridge are approximately one-fourth of its original cost. Therefore, the designer could afford to make other concessions in the design and still have a major economic advantage. It is apparent from tests that such concessions would be minor, if necessary at all. These potential savings make the studies worthwhile.

APPLICATION OF EPOXY SHEAR CONNECTOR

Probably the greatest disadvantage of using an epoxy resin compound as a shear connector is the surface preparation required before applying these materials. All surfaces must be free from dust, dirt, rust, mill scale, latency in the case of concrete, and other surface contaminants. It is not difficult to achieve good clean surfaces, but it may be difficult to maintain this degree of cleanliness before application of the epoxy material.

In the case of the T-beams, all steel I-beams, wide flange, or built-up girder section surfaces must be sandblasted just before the pouring of the deck. After the steel surfaces are thoroughly cleaned by sandblasting, and after the excess blasting grit has been blown from the deck, the steel surface is cleaned with methyl-ethyl-ketone. This final cleaning must be accomplished with lint-, dust-, and grease-free rags or other suitable cleansing materials. The surface is then ready to receive the epoxy compound.

By a suitable applicator (which still needs to be developed) the epoxy compound, which has just been mixed, is applied to a depth of $\frac{1}{4}$ in. to the steel surface. The $\frac{1}{4}$ -in. thickness was selected only after extensive tests showed this thickness to be a minimum requirement if moisture from the fresh concrete is not to penetrate the epoxy and cause rusting of the steel surfaces (5).

After the epoxy compound has been uniformly spread over the steel surface, and washed clean, angular aggregate is placed randomly over the epoxy compound layer. The aggregate should have a maximum size of $1\frac{1}{2}$ in. and a minimum size of 1 in. This material should be placed so as to offer approximately 20 percent coverage of the epoxy surface. No additional effort to force the aggregate into the epoxy layer is necessary after initial placement. The purpose of the aggregate is to increase composite action and to provide the necessary resistance to vertical separation of the slab from the stem. The epoxy compound aggregate surface is now ready to receive the fresh concrete.

The aggregate acts as more than a mechanical shear and vertical tension connector. It actually integrates the concrete with the bonding material so that the mortar matrix

in the regular concrete gradually changes from a cement mortar to an epoxy mortar, culminating in a surface in which strong bond exists between the steel and the epoxy concrete boundary. Thus, the aggregate probably never acts as a mechanical connector in the sense that a steel stud welded to the beam does.

In placing the concrete, the epoxy compound should be covered with concrete as soon as possible after it has been placed. Therefore, no more compound should be applied than can quickly be covered by a layer of concrete. The compound can receive a quick unfinished coverage of concrete; then the normal placement and finishing of the concrete can take place. The steel surface and the fresh concrete on the epoxy will sufficiently retard its curing. No more epoxy compound and concrete should be placed in advance of the normal pouring and finishing process than can be covered before the concrete has taken an initial set.

The epoxy adheres to concrete even though the wet concrete is applied to the wet epoxy compound. But water should not be allowed to penetrate the epoxy compound layer because it forms a film on the steel surface resulting in a rusted area and poor bond between the compound and steel. This water penetration is prevented by using at least $\frac{1}{4}$ -in. thickness of epoxy compound.

EPOXY COMPOUND FORMULATIONS

The epoxy compound used for the shear connector is a definite, precise formulation of an epoxy, flexibilizer-hardener, hardening agent, and inert fillers. Extensive material and adhesive property tests of the formulation and variations of this formulation have been made. Many similar materials have been studied. The formulation described herein is the only one which can be recommended by the authors as suitable for this use, although some uninvestigated formulations may also be adequate. Formulation variation studies (6) have shown that considerable field errors in mixing appropriate proportional amounts can be tolerated without greatly affecting the material properties. However, improper mixing and blending of the ingredients cannot be allowed. For this reason the authors recommend a three-component compound rather than the usual two. To maintain conformity to the usual practices, the formulation is described first as the two-component system.

Two-Component System

<u>Part A</u>		<u>Part B</u>	
<u>Constituents</u>	<u>Parts by wt</u>	<u>Constituents</u>	<u>Parts by wt</u>
Epi-Rez 510	100	Epi-Cure 855	20
Alumina T-60	20	Epi-Cure 87	10
Asbestos 7-TF-1	20	Alumina T-60	20
		Asbestos 7-TF-1	20

Constants.

Wt-gal, resin portion (lb)	11.77
Wt 1 gal, converter portion (lb)	12.93
Wt 1 gal, total (lb)	12.16
Viscosity of total formula at 1 rpm, 77 F (cps)	84,000
Pot lift at 77 F, for a 1-pint batch (min)	35
Gel time in thin film at 77 f (hr)	2.0

Mixing Ratio. —The mixing ratios may be based on the parts by weight of epoxy as listed in the foregoing formulation, or if volume is preferred, the 1-quart resin portion is thoroughly mixed with 1 pint of the converter portion.

Liquid Portions. —Epi-Rez 510 is a standard epoxy resin composed of commercial diglycidal ether of bisphenol A containing no added diluents, solvents or other contaminants. Epi-Cure 855 is a flexibilizer-hardener, and is an aliphatic amide polyamine consisting of the reaction product of a long chain monobasic acid with polyamine. Epi-Cure 87 is a hardening agent, and it is a modified aliphatic polyamine.

Cautions.—The use of rubber gloves, goggles, and protective clothing is necessary where this formulation is handled and used. Areas of the body which come in contact with uncured resin and/or converters should be cleaned with denatured alcohol, then well scrubbed with soap and water.

Three-Component System

Part A		Part B		Part C	
Constituents	Part by wt	Constituents	Part by wt	Constituents	Part by wt
Epi-Rez 510	100	Epi-Cure 855	25	Alumina T-60	40
		Epi-Cure 87	10	Asbestos 7-TF-1	40

Parts A and B are thoroughly mixed by mechanical or manual means. After the mix is complete, Part C is added and thoroughly stirred into the mixture. By this method better chemical reaction is assured, particularly on days with temperatures ranging below the recommended minimum temperature of 60 to 70 F. This three-component system is recommended for use as a T-beam shear connector.

MATERIAL PROPERTIES OF EPOXY COMPOUND

As with any structural material, strength properties are a very important consideration in design. To determine the properties of the epoxy compound (Table 1), various tests were performed according to ASTM standards for plastics, and other tests were developed for determining the properties not covered by the standards. In any case, the methods used for determining the properties of epoxy resins need some revision, as duplication of results is not within close tolerances.

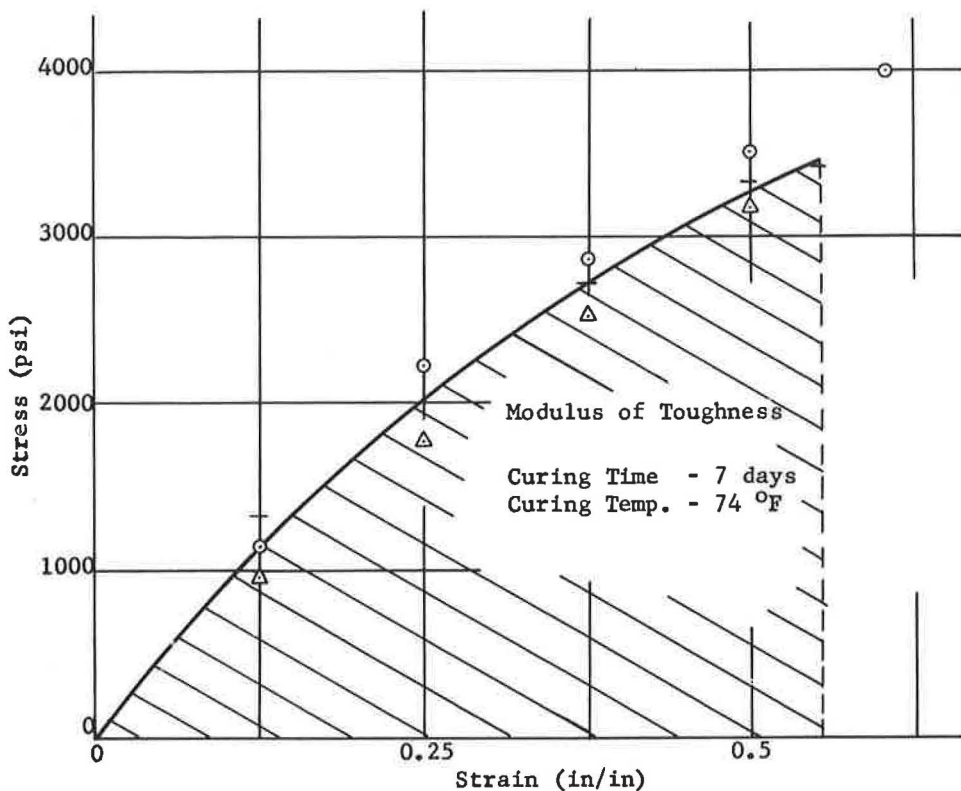
The results of some of these tests follow. The method used is not described in detail, but the proper reference is given for obtaining the test method.

1. Material Tensile Strength.—The material tensile strength was obtained by using a test method similar to ASTM Standard D638-64T. Difficulties in preparing specimens occurred because of the high viscosity of the system being tested. Large air bubbles occurred in the specimens, resulting in stress concentrations and an ultimate strength lower than that obtained for the adhesive tensile strength. The specimens were cast in

TABLE 1
PROPERTIES OF EPOXY COMPOUND SHEAR CONNECTOR MATERIAL

Property	Range of Values ^a
Material tensile strength	3,000 to 4,000 psi
Modulus of elasticity, tension	400,000 to 700,000 psi
Modulus of toughness, tension	10.2 to 20.0 in.-lb/in. ³
Percent elongation	0.5 to 1.2 percent
Material compressive strength	7,000 to 8,000 psi
Proportional limit, compression	5,000 to 6,000 psi
Modulus of elasticity, compression ³	325,000 to 350,000 psi
Adhesive tensile strength	3,000 to 7,500 psi
Adhesive shear strength	1,200 to 2,400 psi
Coefficient of thermal expansion	27.3 × 10 to 32.0 × 10 in./in./deg F
Arizona composite cylinder rating	92 to 102 percent

^aThese values represent a minimum of eight test specimens.



3 Specimens

Ave.

Maximum Stress	3573 psi
Proportional Limit	---
Modulus of Elasticity	572,000 psi
Modulus of Toughness	11.75 in-lb/in ²
% Elongation	0.55%

Figure 1. Epoxy compound tensile strength test.

silicone rubber molds and machined to a smooth finish, with a cross-section $\frac{5}{16}$ in. thick and $\frac{1}{2}$ in. wide. Figure 1 shows the stress-strain curve for the material with the appropriate values listed as obtained from the curve.

2. Material Compressive Strength.—The material compressive strength was run similar to ASTM Standard 695-63T. The specimens, cast in silicon rubber molds were 1 in. in diameter and 1.312 in. high. Figure 2 shows the stress-strain curve with the material properties listed.

3. Adhesive Tensile Strength.—This test was run similar to ASTM Standard D897-49. Two solid steel cylinders with 1-sq in. cross-sectional areas were joined end to end with the epoxy compound. A special jig was used to align the specimens and assure a proper bond-line thickness. The specimens were tested by applying tension on the cylinders, thus placing the bond line in tension (Table 1).

4. Adhesive Shear Strength.—This test was run similar to ASTM Standard D1002-64. Steel strips, 5 in. long by 1 in. wide by $\frac{5}{16}$ in. thick, were overlapped $\frac{1}{2}$ in. and bonded together with a thin coat of epoxy compound. As was the case for the adhesive tensile strength, a special jig was made which assured proper bond-line thickness and proper

alignment of the specimens. The specimen was placed in longitudinal tension resulting in a shear failure at the overlap (Table 1).

5. Arizona Composite Cylinder Test.—This test method was developed in the civil engineering laboratories of the University of Arizona. The purpose of the test is to evaluate effectively materials which will bond wet concrete to hardened concrete or hardened concrete to hardened concrete.

The epoxy compound used as a shear connector must bond in the presence of wet concrete, and if the composite T-beam stem is to be of reinforced concrete, this test method is directly applicable. For the cases where a steel stem is utilized, the test still proves the feasibility of epoxy compound to bond in the presence of wet concrete.

To prepare specimens, half cylinders of concrete which had been cured for at least 30 days were cast in standard 6- by 12-in. cylinder molds in which an elliptical plate had been placed at a 30-deg angle to the vertical axis. The resulting slanted flat surface was treated with a 10 percent solution of hydrochloric acid to remove latent materials and was then thoroughly washed. The epoxy compound was spread on the surface, the cylinder replaced in the mold, and the remaining cavity filled. This resulted in a standard cylinder with an epoxy-compound bond line diagonally cutting it. The results are expressed as a percentage of the strength of a regular homogeneous cylinder cast at the same time. A strength of 90 percent was set as the minimum in which acceptable bond was achieved.

Although specific results are not presented here, this test, now widely used, is an excellent one to use for sorting the many epoxy compounds and selecting the most appropriate. The various compounds divide into two clear-cut groups, those which are clearly inadequate (with a rating of 30 to 40%) and those which have a rating of 90 percent and above (Table 1).

6. Coefficient of Thermal Expansion.—The coefficient of thermal expansion of the epoxy compound was measured by making electrical strain gage readings on a free epoxy specimen undergoing temperature changes. The strain measuring bridge was completed by a dummy gage on silica glass which has a negligible coefficient of thermal expansion (Table 1).

7. Creep, Fatigue and Aging.—Tests were also made to determine whether creep, fatigue and aging properties of the epoxy compound would adversely affect the life of the composite T-beams. The creep and fatigue studies were made on full scale T-beams by subjecting them to sustained loads and repeating loads, respectively. At normal working load conditions no measurable creep was noted for loads maintained for as long as one week. The epoxy-joined T-beams did not suffer from fatigue loading (8).

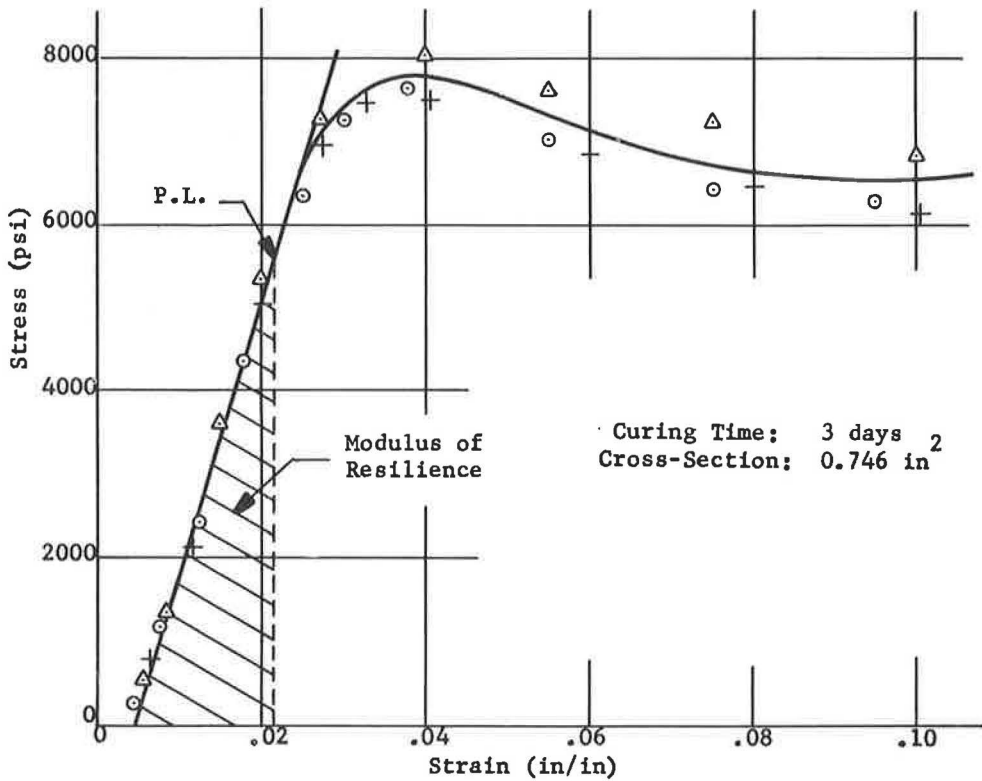
Studies of the epoxy are very complex and far from being conclusive. Nevertheless, those performed to date have shown that the particular epoxy system being used as a shear connector is quite stable with time.

DESIGN AND PROPERTIES OF T-BEAMS

Thirty-one T-beams, 26 of which used an epoxy compound shear connector, were tested statically. Test results of 10 of these beams are presented in this paper. Of these, 6 beams utilized the most successful of the epoxy compound shear connectors tried, and were prepared according to the aforementioned procedures. Four of the beams utilized an equivalent mechanical shear connection (studs) for comparison purposes. The T-beam dimensions and properties are given in Table 2.

All of the T-beams were "biased" in design to produce high shear stresses in the epoxy compound bond line. This was done by sizing the slab and steel beam so that the neutral axis occurred close to the shear connection, and also by selecting steel sections with a relatively narrow flange width. Both of these factors tended to maximize the shear stresses at the joint.

Property tests of many types of epoxy resin compounds have shown that one must be very selective to achieve good resistance to shear when bonding to steel. This is particularly true where impact loading is applied. The compound selected has sufficiently high tensile strength and meets the minimum requirements of shear strength. The steel-to-steel shear strength is approximately 2,200 psi with occasional specimens



3 Specimens	Ave.
Maximum Stress	7740 psi
Proportional Limit	5570 psi
Modulus of Elasticity	340,000 psi ³
Modulus of Resilience	46.50 in-lb/in

Figure 2. Epoxy compound compression test.

TABLE 2
T-BEAM DIMENSIONS AND PROPERTIES^a

T-Beam	Length (ft)	Steel Beams Size	Slab Dim. Size (in.)	Moment of Inertia, I	Modular Ratio, n	Yield Strength (psi)	f'_c (psi)	Neutral Axis, N. A. (in.)	Shear Span, a (ft)
A2-1	21	8I23	4 × 29	245	7.02	43,000	5,470	3.97	6.5
A4-1	29	15I50	4 × 40	1,327	6.73	38,400	5,580	5.63	10.0
C1-1	11	8WF17	3 × 24	150	6.10	46,000	4,670	3.48	3.0
C1-IS ^b	11	8WF17	3 × 24	170	6.35	46,100	4,470	3.18	3.0
C2-1	21	8I23	4 × 24	245	7.00	37,900	4,740	3.97	6.25
C2-IS	21	8I23	4 × 24	268	5.06	39,400	4,720	3.57	6.25
C3-1	21	12I50	4 × 40	849	6.64	39,300	4,230	5.52	6.25
C3-IS	21	12I50	4 × 40	902	7.00	35,900	4,690	5.11	6.25
C4-1	29	15I50	4 × 40	1,255	6.38	36,900	4,370	6.10	10.5
C4-IS	29	15I50	4 × 40	1,340	6.50	39,300	4,410	5.55	10.5

^a I = moment of inertia of cross-section, computed from transformed section;

n = ratio of modulus of elasticities of steel and concrete;

f'_c = compressive strength of concrete at time tests;

N.A. = computed neutral axis of cross-section measured from top of beam; and

a = shear span, measured from support to location of load (two symmetrically placed jacks provided load).

^b IS following T-Beam identification indicates a mechanically connected T-beam; other T-beams employed epoxy shear connector.

failing as low as 1,240 psi. These strength values were also obtained using other epoxy compound systems. However, the selected system was the only one which showed sufficient resistance to impact loading.

The data for several preliminary T-beams are not presented here. These had varying bond-line thickness, epoxy compounds, and surface treatments used in the shear connection. In general, these beams failed at the shear joint due to poor bond between the steel and the epoxy compound. These were largely pilot tests to investigate various combinations of materials, and to study the general behavior of the beams. A2-1 and A4-1 were the first beams made which performed adequately at loads beyond the yield point of the steel. These beams used the recommended epoxy compound formulation with a $\frac{1}{4}$ -in. thick joint and the scattered aggregate treatment previously described.

There was considerable difference in the performance of the pilot beams, depending on the thickness of the shear joint. A special investigation was initiated to study the thickness effect, but the results were of qualitative value only. A round steel specimen was machined to a 4-in. diameter and a 1-in. thickness with one surface ground highly smooth. The plate was placed inside a standard 6- by 12-in. cylinder mold in such a way that a half cylinder (6×6) could be cast on top of it, and was coated to a uniform depth of either $\frac{1}{16}$, $\frac{1}{8}$, or $\frac{3}{16}$ in. with epoxy compound. Either no aggregate was applied to the surface, or a 20 percent coverage of $\frac{3}{8}$, $\frac{3}{4}$, or $1\frac{1}{4}$ -in. aggregate was applied. The plates were then pulled off in a testing machine, and the tensile strength of the joint recorded.

The $\frac{3}{16}$ -in. epoxy joint with the $1\frac{1}{4}$ -in. aggregate coverage gave the best result. The failure was always by rupture of the concrete in this case at an average stress of over 4,000 psi for all joints with the $\frac{3}{16}$ -in. thickness regardless of the aggregate size used. The $\frac{1}{16}$ -in. coating gave results averaging about 2,500 psi. The thinner coatings showed water penetration, rusted areas on the steel plate, and the resulting poor bond. The aggregate size seemed to have a less pronounced effect. Figures 3 and 4 show the difference in types of failure for different thicknesses. As a result, a $\frac{1}{4}$ -in. coating and

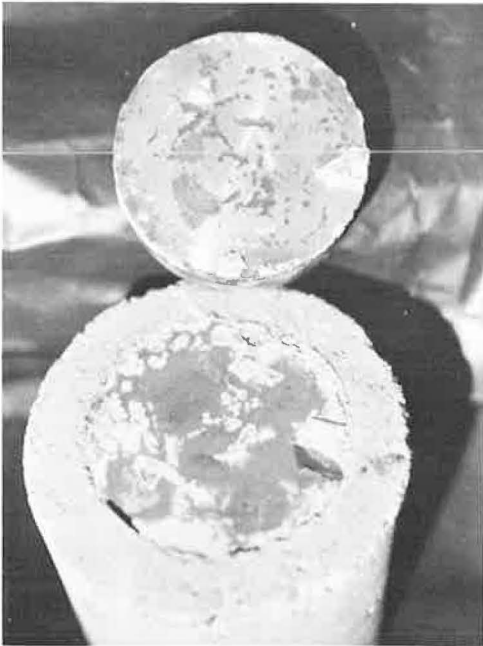


Figure 3. Concrete-to-steel tension test showing effect of moisture penetration through epoxy compound: rusting of steel, and areas of compound turned white by moisture.

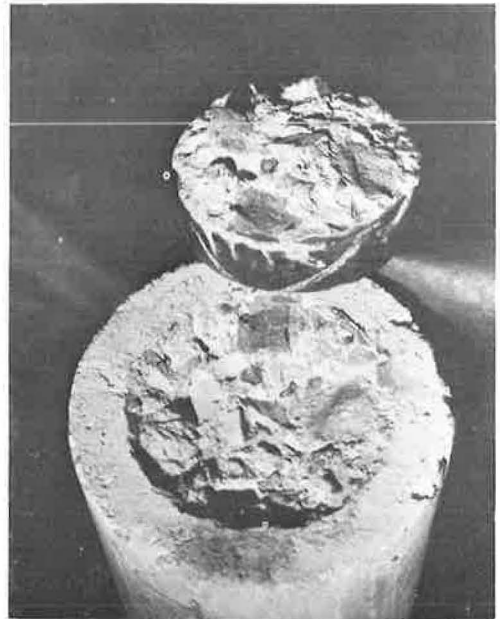


Figure 4. Concrete-to-steel tension test showing $\frac{3}{16}$ -in. bond line resulting in concrete failure, and unruptured white line between epoxy compound and concrete.

TABLE 3
T-BEAM TEST DATA

T-Beam Connector	Ultimate Load			Shearing Stresses			Maximum Bond-Line Slip (10^{-4} in.)	Type of Failure
	Computed Kips	Test Kips	Ratio: Test/Computed	Theoretical Yield (psi)	Theoretical Ultimate (psi)	Avg. Experimental Ultimate (psi)		
A2-1 Epoxy	21.8	22.9	1.05	390	770	925	35	Flexure-shear
A4-1 Epoxy	42.7	39.6	0.93	368	790	600	9	Flexure-shear
C1-1 Epoxy	37.0	35.3	0.95	494	1,215	1,160	36	Shear
C1-1S Mechanical (stud)	36.8	39.2	1.06	594	1,220	—	290	Flexure
C2-1 Epoxy	22.6	22.2	0.98	319	814	799	23	Flexure-shear
C2-1S Mechanical (stud)	23.3	23.5	1.01	452	842	—	570	Flexure
C3-1 Epoxy	61.2	46.9	0.77	657	1,393	1,068	8	Shear
C3-1S Mechanical (stud)	58.4	57.7	0.99	586	1,280	—	304	Shear
C4-1 Epoxy	41.4	41.4	1.00	334	757	757	10	Flexure-shear
C4-1S Mechanical (stud)	43.6	41.4	0.95	366	807	—	290	Flexure

20 percent coverage with $1\frac{1}{4}$ -in. aggregate were selected for the shear joint for the rest of the tests (C series). The T-beams of groups C1 and C3 were designed to induce shear stresses approaching the minimum adhesive shear value of 1,200 psi at ultimate load. The T-beam of groups C2 and C3 were designed to have shearing stresses in the neighborhood of one-half the former value. Variance in concrete and steel properties led to the values given under "theoretical ultimate shearing stresses" (Table 3). These values are, at best, only a conservative estimate, because there is no theory which is accurate for calculating them.

TESTING PROCEDURE

The T-beams were loaded by two hydraulic rams placed symmetrically about the midspan of the beams. A small load was first applied to assure complete initial settlement of the T-beam and the supports. The supports were rollers placed 6 in. from the



Figure 5. T-beam test setup.

ends of the beam. The shear span, a , the horizontal distance from the support to a loading jack, is given in Table 2. After removal of all but a small "holding" load, zero readings were made on all gages. All of the beams were instrumented to measure deflection and strain distribution at midspan and end slip of the slab in relation to the steel beam. Some beams were instrumented to measure bond-line slip along the length of the beam-strain distribution across the top and bottom of the slab, and to measure strains in the shear span.

The load was applied in increments, and data readings were taken after each increment. The loads were continually increased until complete failure of the specimen occurred. The test setup is shown in Figure 5.

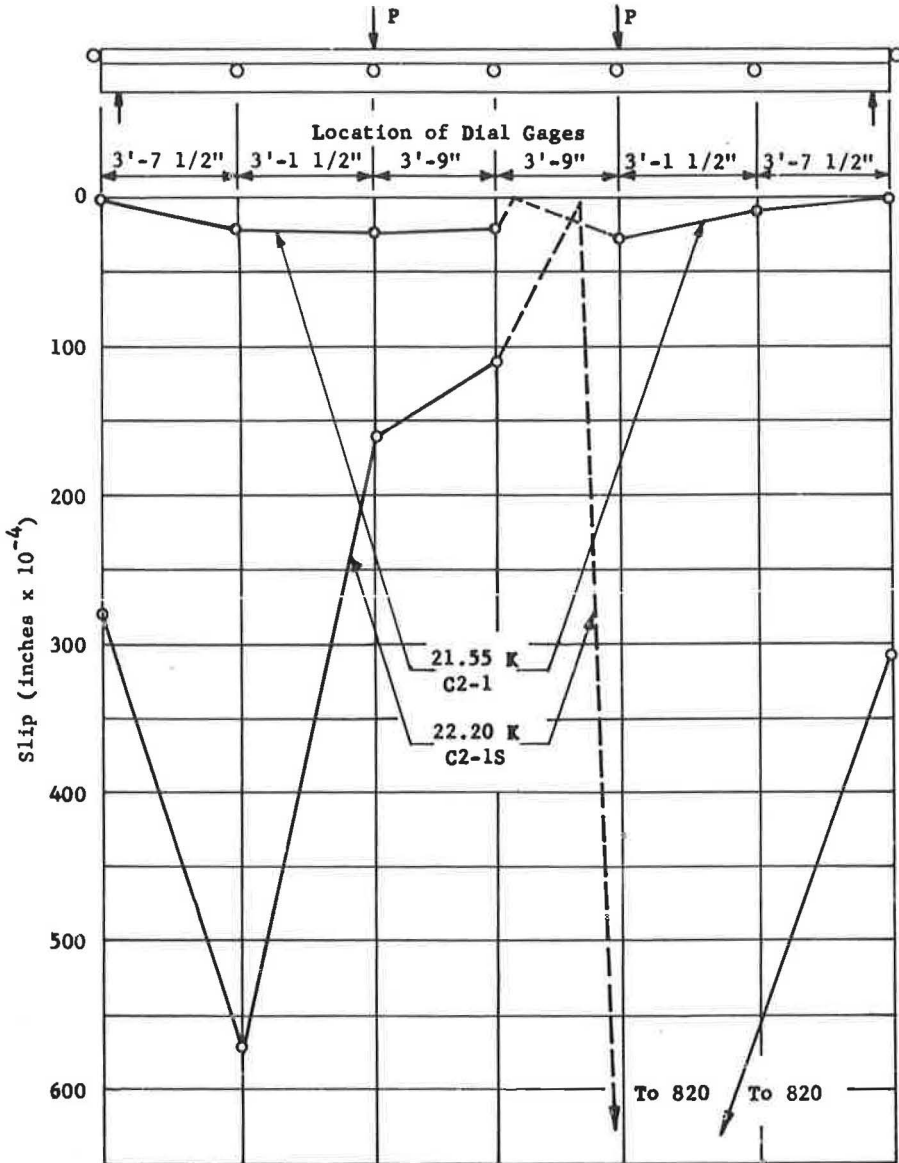


Figure 6. Comparison of load-slip curves at ultimate load for beams C2-1 and C2-1S.

TEST RESULTS AND CONCLUSIONS

The test results are given in Table 3, with data for each epoxy-compound joined T-beam followed by data for the equivalent mechanically connected T-beam. A direct comparison can be made of ultimate loads, shearing stresses, and bond-line slip. All of the T-beams behaved under load as expected. The epoxy T-beam with the highest ultimate shear stress, C3-1, failed at the lowest load. This is indicated by the 0.77 ultimate load ratio. This T-beam initially failed by shear of the epoxy from the steel throughout the shear span. The mechanically connected T-beam C3-1S behaved normally under loading, and the theoretical ultimate load was reached before complete failure occurred. This set of T-beams indicated that for high shear stresses, mechanically connected T-beams are best as far as developing the ultimate strength of the steel beam is concerned, at least for the "biased" design beams tested. It also demonstrated that shear stress is an important criterion when designing an epoxy-joined T-beam.

Epoxy-joined T-beam C1-1 had the second highest theoretical ultimate shear stress. The ratio of the ultimate loads for this T-beam was 0.95 which indicates excellent performance. The corresponding mechanically connected T-beam performed adequately as is indicated by the 1.06 load ratio. The T-beam C1-1 actually had a higher average experimental shear stress. Realizing that these values are only an estimate based on conventional theories and considering the range of values obtained by the bonding shear strength tests, it can be surmised that both T-beams C1-1 and C3-1 were in a critical load range. Complete failure could occur suddenly within a fairly wide range of load values.

Of the other two groups, C2 and C4, the epoxy-joined T-beams carried as great a portion of the theoretical ultimate load as was carried by the mechanically connected T-beams. The shearing stresses at ultimate load were well below the critical range. The two epoxy-joined T-beams of these groups failed by a combination of shear and flexure action. A longitudinal crack developed in the slabs of each of these T-beams near the time of failure. It is not known which occurred first, the crack or shear failure. This longitudinal crack is common when testing mechanically connected T-beams,

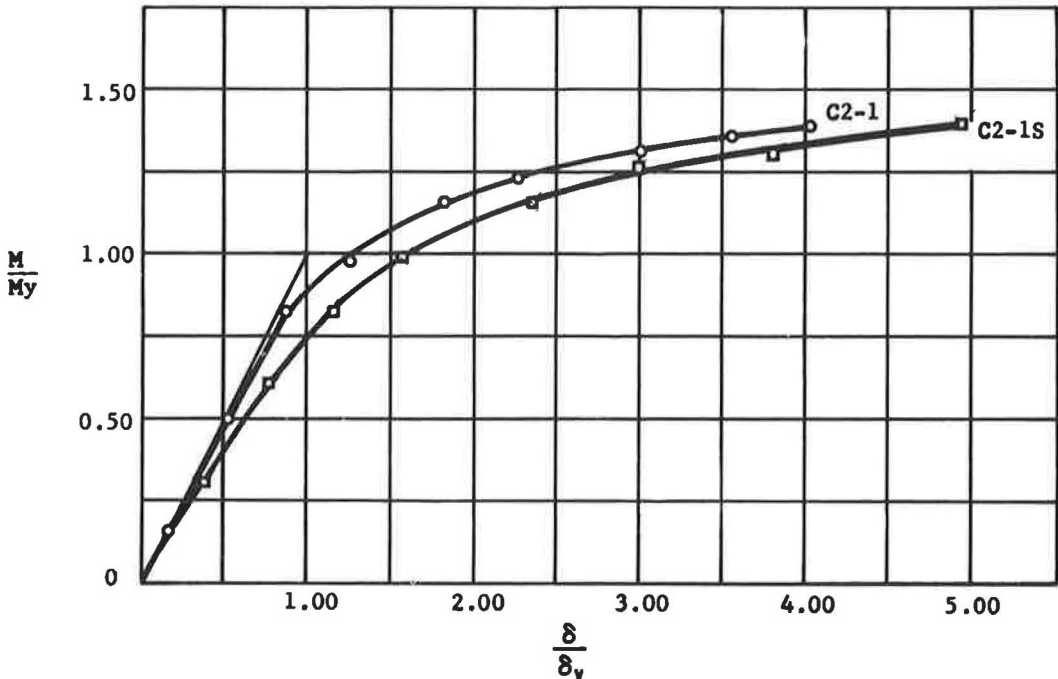


Figure 7. Comparison between deflection curves, beams C2-1 and C2-1S.

and is the first sign of failure of the concrete slab when ultimate load has been reached. In this case, however, studs do prevent the slab from coming completely free of the steel beam. The theoretical ultimate loads (based on the development of a complete plastic hinge in the steel) of the T-beams in the groups C2 and C4 were reached.

The effectiveness of the epoxy resin compound in developing more integral beam action than the mechanical connectors is probably best illustrated by the bond-line slip. All T-beams were instrumented so that the relative movement of the slab with respect to the stem could be measured. The maximum slip measured before failure in an epoxy T-beam was only 0.0036 in., whereas the highest slip for a mechanically connected T-beam was 0.0570 in. The slip in the mechanically connected T-beams was from 8 to 30 times as high as that in the epoxy-joined T-beams. A typical set of slip-load curves (beams C2-1 and C2-1S) is shown at ultimate load in Figure 6.

Figure 7 shows a typical dimensionless deflection curve comparison for beams C2-1 and C2-1S. The epoxy-joined beam is stiffer than the mechanically connected beam, and in every case followed the theoretical deflection curve in the elastic region, indicating more integral behavior between the beam and the slab. Also, the epoxy-joined T-beam always carried more load for a given deflection value. Thus the mechanically connected beam had more toughness, but the epoxy-connected beam acted more elastically.

A study of a wide variety of composite T-beam designs shows that shear stresses in the slab-beam joint seldom exceed 200 psi in normal applications. The ultimate experimental shearing stresses achieved in the test beams ranged between 600 and 1,160 psi. Thus the safety factor was no lower than 3 and ranged as high as 6. Inasmuch as these shear failures were closely associated with the yield of the steel and the development of a full plastic hinge, they would undoubtedly exceed these values in other cases.

Of prime importance is the ability of these T-beams to withstand fatigue and impact loading. As previously indicated, impact was one of the primary considerations in selecting the epoxy resin system. Eight composite T-beams were subjected to fatigue; six were epoxy-compound connected, and the other two were mechanically connected. They were of the same design as those previously mentioned. It is beyond the scope of this paper to report the complete dynamic testing and behavior of these beams. However, none failed under dynamic loading. Some of the epoxy-joined beams endured as many as 7,000,000 cycles without any significant change in bond-line slip or deflections. They underwent load cycling which varied from 200 to 250 cpm. The maximum and minimum load, expressed as shear stresses in the epoxy-compound joint, varied from 150 to 300 psi. The flexure stress in the steel ran as high as 41,500 psi during some of this testing.

CONCLUSION

An epoxy resin compound can serve as a reliable and safe shear connector for composite T-beams. The epoxy resin formulation and method of applying this formulation have been described. Test results indicate that very successful behavior of these epoxy-joined T-beams can be expected under long-term loading, either static or dynamic. The shear stress in the epoxy joint is a prime consideration when designing the T-beam. Economic considerations due to its minimizing shrinkage cracks and consequent bridge-deck deterioration may give it a great advantage over mechanical connections. It is not recommended that design specifications be written at this time. However, further work leading to design criteria should be carried out, and the contention that T-beams can be designed as monolithic units without regard to the shear connector when the recommended epoxy compound is used should be further substantiated.

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