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Abridgment

Repair of Torsionally Inadequate Concrete Beams by Use of Adhesively Bonded Plates

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The results of a study conducted to determine the feasibility of repairing torsionally inadequate reinforced concrete beams by using externally bonded steel plates are presented. The test program consisted of three sets of beams. Set A consisted of beams that had failed under torsional loading. Set B consisted of the same beams that failed as set A but were repaired by using epoxy adhesive to bond plates to the sides of the beams in the exterior thirds of the beam span. For set C, the plates were bonded to the sides of the beams before any testing. In the repaired beams, the external plates not only restored the integrity of the failed members but also increased the load-carrying capacity by 20 percent. For equal loads, the repaired beams had deflections approximately 6 percent less than those of the original beams. Set C, the control set, had 20 percent more carrying capacity than the concrete beams and also had deflections 20 percent lower. However, the plate configuration used did not force the members to fail in a flexural mode. The repair method was shown to be feasible, but more research is recommended to determine the best plate configuration and plate size.

The use of externally bonded steel plates to strengthen reinforced concrete beams is not new. Fleming and King (1) in South Africa have used bonded plates in the tension zone of concrete beams. Irwin (2) in the United Kingdom has done similar work. In the United States, at least one bridge in California has been strengthened by Byrd, Tallamy, MacDonald, and Lewis. However, all of these applications have been directed toward increasing the flexural capacity of the members.

Until this time, no work has been done on increasing the torsional capacity of reinforced concrete members. One principal type of structure that exhibits torsionally inadequate spandrel beams is the parking garage. Typically, the facade of a garage with several bays will be surrounded by spandrel beams, and very heavy loads, such as automobiles, will be parked at some distance from the spandrel beam. This loading produces a torsional moment, which in turn produces torsional stresses in the spandrel beam. Depending on the location in the member, these torsional stresses can add to the shear stresses.

Most prior testing of torsionally loaded members has been for the analysis and design of new members, but very little information is available on the repair of torsionally inadequate members.

OBJECTIVE OF THE PROGRAM

The objective of this study was to propose a method of repair for torsionally inadequate reinforced concrete spandrel beams. The proposed solution was to adhesively bond steel plates to the vertical faces of the beams in the high-shear and high-torsion regions by using an epoxy adhesive. The intent was to entirely control the torsional cracking of the member and shift the mode of failure from sudden torsional failure to a more conventional flexural failure with a forewarning of collapse.

DESIGN OF THE EXPERIMENT

The reinforced concrete members were designed in accordance with the American Concrete Institute (ACI) code and commentary (3,4). The relation between the test sections and the actual building framing is shown in Figure 1. The test members were modeled to represent a typical spandrel beam located between two adjacent columns and supporting a floor beam at each of the third points. In an actual building, a monolithically cast slab would complete the system. However, in order to better study the pattern of crack formation, the slab was omitted from the members in the testing program. The beams were specifically designed so that the mode of failure would be in torsion. For the experiment, the model was mounted so that it performed as a pinned connection with respect to flexure and normal shear and as fixed with respect to torsion.

The spandrel beams tested were 4x8 in (102x203 mm) in cross section and 9.5 ft (2.9 m) long. Four no. 6 bars of grade 60 steel were used as longitudinal reinforcement. The stirrups were 0.187 in (5 mm) of grade 40 steel. The steel plates, which
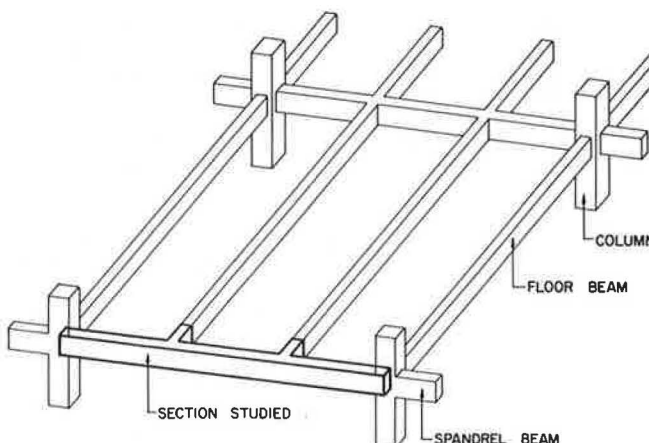
Figure 1. Test specimen.
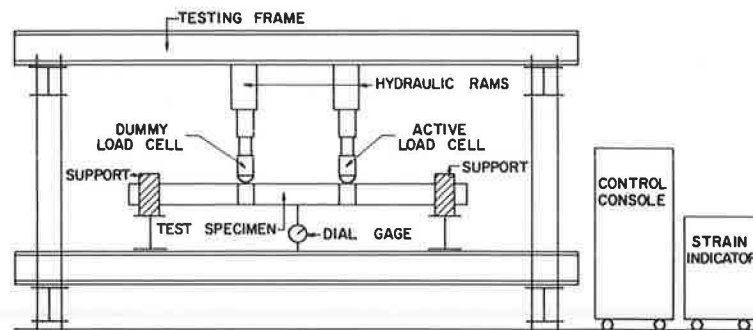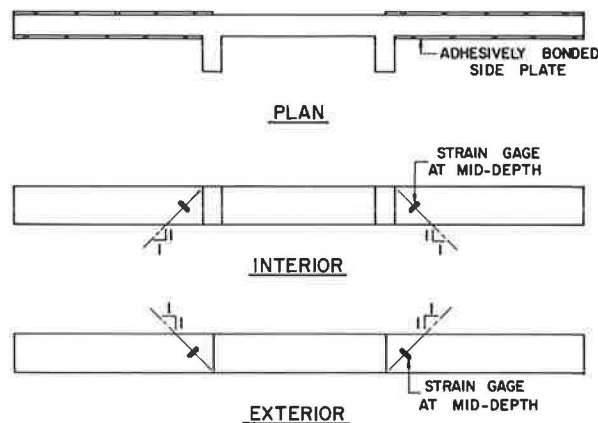
Figure 2. Testing arrangement.

Figure 3. Strain-gage locations.

PLAN

STRAIN GAGE
AT MID-DEPTH

INTERIOR

STRAIN GAGE
AT MID-DEPTH

EXTERIOR

were used only in the outer thirds of the beam, were A-36 steel 0.187 in thick.

The design strength of the concrete was 5000 lbf/in² (36 000 kPa). However, the concrete actually used in the project had a 28-day strength of 8500 lbf/in² (61 000 kPa) and a slump of 2.5 in (64 mm).

In total, nine beams were tested to evaluate the performance of the proposed composite rehabilitation system. Set A consisted of three beams designed to fail in a combined normal and torsional shear failure in the exterior third of the spans. Set B consisted of the repair beams that initially failed as beam set A. Set C consisted of the control set. These were beams to which bonded plates were attached prior to any testing for observation of full composite action.

TESTING PROCEDURE AND INSTRUMENTATION

The beams were mounted for testing in the loading frame as shown in Figure 2. Load was applied simultaneously to the two short cantilever stubs by an electronically controlled hydraulic ram system.

Since this experiment was the initial one of its kind, only an elementary amount of instrumentation was used. Three types of observations were made during the testing program:

1. The centerline deflection was monitored for all beams by using a dial gage incremented to the nearest 0.001 in (0.025 mm).
2. The crack patterns were carefully monitored for all beams to serve as a warning of impending failure.
3. Strain gages were used to evaluate the performance of the steel plates during the testing of beam sets B and C. Four strain gages were used on

each beam. They were positioned and oriented on the beams in a direction perpendicular to the anticipated crack formation. The locations of gages are shown in Figure 3.

LOADING

The load was applied in 200-lbf (0.89-kN) increments equally to each cantilever at a rate of 10 lbf/s (0.045 kN/s) for the first specimen in each beam set. For subsequent beams in each set, the load was applied in 400-lbf (1.78-kN) increments at a loading rate of 10 lbf/s. At each 400-lbf increment, the strain and deflection variations were allowed to stabilize for a 3-min period. During this time span, a close visual inspection of the beam was made for cracks that would indicate impending failure. Strain gage and deflection readings were made at both the beginning and the end of this period. This procedure was repeated until a load of 4000 lbf (17.8 kN) was being applied to the specimen. At that point, the procedure was changed so that 200-lbf increments were applied up to failure. Failure was determined as the load at which a torsionally induced concrete rupture occurred or a point at which deflections were visibly increasing without increasing the loading. For the protection of the technicians and the equipment, the dial gage was removed when centerline deflection approached 0.5 in (13 mm).

RESULTS

The program showed that it is feasible to repair torsionally inadequate beams by using bonded side plates. However, the specific method of repair used in this program is not the complete answer.

Two positive effects and one negative effect were shown by the program. The failure load of the composite sections was 20 percent higher than that of the noncomposite members. In addition, excellent results were seen in the area of crack observation as a means of identifying the mode of failure. For all specimens in beam set A, the failure occurred in the classical torsional crack mode in the exterior thirds of the span. Although no new torsional cracks were observed on the top or bottom of the beams in the area of the bonded plates, the torsional stresses still remained to be accounted for. The bonded side plates forced a redistribution of stresses, which in turn forced the torsional stresses into the interior third of the span. Consequently, at a point at which no torsion failure was expected, a large torsional crack formed that led to a sudden failure of the specimens. This failure was sudden and explosive. It was not uncommon for pieces of the concrete to fly several feet from the specimen at failure. This is precisely the type of failure the investigators were trying to avoid.
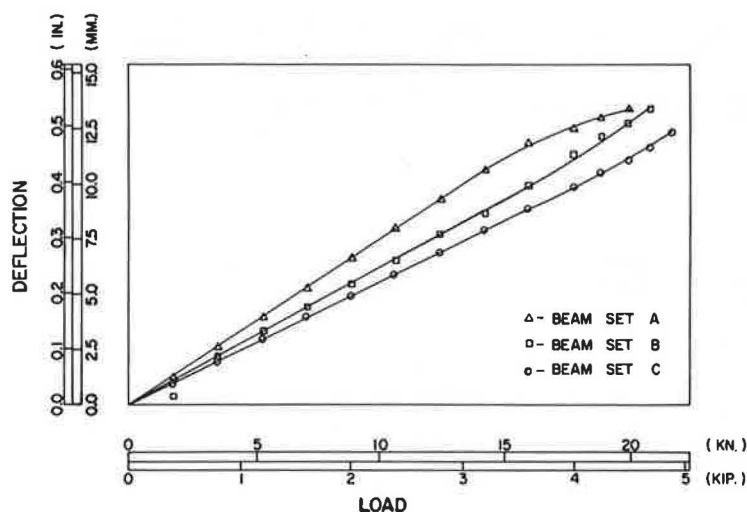
Figure 4. Load deflections.

Table 1. Test results.

Beam	Max Load (kips)	Mode of Failure
A1	8.80	Combined normal and torsional shear
A2	8.80	Combined normal and torsional shear
A3	7.20	Combined normal and torsional shear
B1	10.10	Torsionally induced shear cracking
B2	10.40	Flexure in floor beam cantilever
B3	9.20	Torsionally induced shear cracking
C1	9.20	Torsionally induced shear cracking
C2	10.30	Torsionally induced shear cracking
C3	10.00	Torsionally induced shear cracking

Note: 1 kip = 4.45 kN.

A preliminary judgment might be that the side plates had yielded. However, examination of the maximum strains in the plates showed that the stresses in the plates were well below yield. Consequently, thinner plates might be used.

A study of the deflections (see Figure 4) shows that the ultimate deflections of all of the beams were grouped quite closely. However, when the deflections at the ultimate load are compared, beam set A shows that the repaired beams not only restored the integrity of the failed specimens but also decreased deflections by 6 percent. At this same load, the control specimens had deflections 20 percent less than those of set A.

Table 1 gives the ultimate load and mode of failure of all the test specimens. The lower load for beam C1 is explained by the fact that the only adhesive failure between beam and plate occurred for this beam. It is worth noting that this was the first plate attached by the technicians.

CONCLUSIONS AND RECOMMENDATIONS

As a result of the program described in this paper, it has been concluded that the use of adhesively bonded plates to rehabilitate torsionally inadequate beams is feasible. However, more analysis and test-

ing are required in order to determine the plate configuration that will suppress torsional failure and force a yield failure in the tensile mode at a predicted load.

In a further testing program, the following steps should be taken:

1. A floor slab cast monolithically with the floor beams and spandrel beam should be included in the test.
2. The method of repair should be bonded plates on both sides of the spandrel beam for its entire length.
3. The plates should be of a smaller thickness to permit plate yielding.
4. A two-span model should be investigated in order to provide a better understanding of the interaction at the interface between column and spandrel beam.

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