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Reinforcement lap failures, September 1964

R. G. Adams
D. A. VanHorn

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Continuously Reinforced Concrete Pavements
Report No. 8

REINFORCEMENT LAP FAILURES

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R. G. Adams
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ERRATA

p. 2 (line 2) change "present" to "prevent".
p. 7 (paragraph 2, line 3) change "72,5000" to "72,500".
(line 4) change "102,500" to "102,200".
p. 8 (paragraph 2, line 2) change "diales" to "dials".
Abstract (paragraph 2, line 2) change "load cycles" to "strain cycles".
(line 3) change "load cycles" to "strain cycles".
(line 7) change "loading" to "strain".
Continuously Reinforced Concrete Pavements

REINFORCEMENT LAP FAILURES

by
R. G. Adams
D. A. Van Horn

An Investigation Sponsored by
PENNSYLVANIA DEPARTMENT OF HIGHWAYS
U. S. DEPARTMENT OF COMMERCE
BUREAU OF PUBLIC ROADS

Fritz Engineering Laboratory
Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania

September, 1964

Fritz Engineering Laboratory Report No. 289.1
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This report describes a series of load tests on reinforced concrete slab specimens designed to simulate sections of continuously reinforced concrete pavement. The specimens were 22 feet in length and 8 inches in depth. A total of six specimens were tested, four reinforced with two No. 5 deformed, hard grade, reinforcing bars (Series A), and two with deformed welded wire fabric having three longitudinal D18.4 wires (Series B). The width of the Series A slabs was 13 inches while that of the Series B slabs was 11 1/2 inches, resulting in a steel percentage of 0.60% for all specimens. The reinforcement was overlapped to form a splice at mid-length in all specimens. In Series A, two of the specimens had overlaps of 18 inches, the other two, 16 inches. Both specimens in Series B had overlaps of 18 inches.

All of the specimens were subjected to the same test program which consisted of three load cycles and an ultimate load test. The load cycles were designed to simulate temperature effects which might be encountered in the State of Pennsylvania. The failure criteria was based on width of crack at the splice during the load cycles - if the width of the crack reached 0.1 inch, failure had occurred. All of the specimens successfully withstood the three cycles of loading and the performances during the ultimate load tests were all satisfactory. In the ultimate load test, none of the Series A test slabs developed a crack width of 0.1 inch prior to failure, while in both Series B slabs, crack widths slightly exceeded 0.1 inch in the last load increment.
before failure occurred. Results of the tests indicate that an overlap length of 16 inches is adequate for the No. 5 hard grade bars, and that a length of 18 inches is adequate for the deformed welded wire fabric used. These tests were not designed to determine minimum overlap lengths, only to evaluate the lengths prescribed by the initially outlined program.
1. INTRODUCTION

Several failures in the experimental continuously reinforced concrete pavement on Route 22 near Hamburg, Pennsylvania, have occurred within the lapped region of the deformed bar mats used for reinforcement. The failures were initiated by the formation of cracks which at first appeared to be normal transverse cracks. However, during the first winter after the construction of the pavement, the failure cracks opened excessively, deterioration of the pavement was rapid, and early maintenance and eventual extensive repairs were required. In studies of continuously reinforced concrete pavements in Maryland, similar failures were observed at several locations, with the formation of pairs of rather wide cracks at laps in the reinforcement.

In addition to the Pennsylvania and Maryland investigations, field tests in other states, as well as a laboratory study at Lehigh University, have emphasized the need for more information concerning the structural behavior of continuous pavements in the regions at the laps of the reinforcement. Recently, laboratory studies conducted at the University of Maryland*, and by Wiss, Janney, and Associates, in

---

have served to narrow the range of lap length required to present pavement failures in the area of the lap.

In February, 1963, a meeting attended by representatives of the Pennsylvania Department of Highways, the Bureau of Public Roads, and Lehigh University, was held for the purpose of defining the scope of a laboratory research program necessary to yield data to support the establishment of definite lap requirements for continuously reinforced pavement construction. In the meeting, the following laboratory program was outlined in detail.

Test Program

Specimens:

In general, the test specimens will be 22 feet in length, and will have a rectangular cross section 8 inches in depth. The width will be such that the percentage of steel will be 0.6%, and will be dependent upon the type of reinforcement. Two series of specimens will be fabricated: Series A, which will be reinforced longitudinally with two No. 5 reinforcing bars, and Series B, which will be reinforced with deformed welded wire fabric. In both series, the reinforcement will be lapped at mid-length, and a crack will be pre-formed at the middle of the lap by inserting a plate which will extend from the reinforcement at mid-depth to the bottom surface. The concrete will be

* CRSI Committee on Continuously Reinforced Concrete Pavement. Test Investigations Lap Splices of Reinforcing Steel in Continuously Reinforced Concrete Pavement, Bulletin No. 3, May, 1963
in accordance with Pennsylvania standard specifications for paving concrete, and will have 4 to 6% entrained air and a slump of 2 to 2\(\frac{1}{2}\) inches. A vibrator will be used in placing the concrete.

Testing:

Testing of the specimens is to begin at the age of one day. At that time a longitudinal strain will be introduced which would be equivalent to a temperature drop that might be expected in a 24-hour period (35 degrees). The strain will be introduced in increments at half-hour intervals such that the total strain is attained at the end of two hours. The total strain will be maintained for a period of four hours, then reduced in half hour increments, to complete relaxation at the end of two hours. A similar procedure will be used when the specimen is two days old, except that the strain will represent an expected temperature drop over a 2-day period (42 degrees). Likewise, on the third day the specimen will be subjected to a strain equivalent to an expected temperature drop over a 3-day period (50 degrees). The values of the temperature differentials used for the one, two, and three day periods were determined from an examination of daily temperature records in Pennsylvania.

If the pre-formed crack at the lap opens as much as 0.1 inch, the specimen will be set aside at the end of the 3-day testing program for further curing, and will later be subjected to strain cycling at increasing strain increments until complete failure occurs. If the pre-formed crack does not reach a width of 0.1 inch during the 3-day
testing program, the lap will be considered successful, and the specimen will be tested to failure.

Series A - Reinforcing Bars:

The first two specimens will be identical, and will have a lap length of 18 inches. If the test results are similar, no further testing with this lap will be done. If the test results are not similar, a third specimen will be tested. A second group of two (or three) specimens, will be tested, based on results of the first group of tests. If the 18-inch lap is adequate, the second group will have a lap length of 16 inches, if inadequate, 20 inches.

Series B - Welded Wire Fabric:

A similar program is to be conducted with specimens reinforced with deformed welded wire fabric. The length of lap will be 18 inches for the first group of two (or three) specimens. If the tests of the first group of specimens indicate that the 18-inch lap is adequate, no further tests will be made. If the 18-inch lap proves to be inadequate, a second group, having a lap length of 27 inches, will be tested.
2. DESCRIPTION OF TESTS

2.1 Specimens

2.1.1 Major Details

Series A: Four specimens were fabricated and tested in the A-Series. All specimens were 22 feet in length and had a rectangular cross-section 8 inches in depth and 13 inches in width. The reinforcement consisted of two No. 5 deformed bars each of which was lap-spliced at mid-length of the specimen. The resulting steel percentage was 0.60%. In the first two specimens (A-1 and A-2) the lap length was 18 inches, and in the second two (A-3 and A-4), 16 inches. To aid in the formation of a crack in the lap region, a thin steel plate was located at the center of the lap. The plate was 13 inches wide and extended from the reinforcement to the bottom surface of the specimen.

Series B: Two specimens were included in the B Series. The length and depth of the specimens were identical to those of the A-Series, but the width was 11½ inches. The reinforcement consisted of two sections of deformed welded wire fabric lap-spliced at mid-length with an 18-inch lap. The deformed wire fabric was made up of 3 longitudinal D18.4 wires spaced at 4½ inches. The transverse wires were ¼ inch in diameter and spaced at 12 inches. The steel percentage was 0.60%. In both specimens (B-1 and B-2) the lap length was 18 inches. As in Series A, the thin steel plate was placed at the center of the lap.
The details of the specimens for both Series A and Series B are shown in Figure 1.

2.1.2 Construction Procedure

The forms for the test specimens were constructed of 3/4-inch plywood. The bottom form was placed directly on the floor of the laboratory, and the side forms were attached by means of angle cleats and wood screws. To minimize frictional resistance during loading and unloading, a strip of rubber, $\frac{1}{2}$ inch in thickness, was placed in the bottom of the form and topped with a single layer of roofing tar paper. The main reinforcement was supported at mid-length by the thin steel plate, at the quarter points by high chairs, and at the ends by the end forms. At each end, six No. 3 deformed bars were embedded longitudinally to serve in attaching the loading and anchorages fittings. Also at each end, five stirrups, shaped from No. 2 bars, formed a cage with the six No. 3 bars. Details of the specimens are shown in Figure 1.

The concrete was placed with the aid of an internal vibrator. After the concrete had been placed, wet burlap was used to cover the exposed surface, and a plastic sheeting was placed over the entire form. The side and end forms, burlap, and plastic sheeting was removed when the concrete had aged 22 hours.

A total of thirty 6 x 12 test cylinders were cast with each test specimen. Twenty-four of the cylinders were cured next to the test specimens. The remaining six were placed in a curing room maintained at 70°F and 100% relative humidity.
2.1.3 Materials

The concrete was supplied by a local ready-mixed concrete firm in accordance with the standards for paving concrete prescribed by the Pennsylvania Department of Highways. The weights of the materials for a one-yard batch were as follows:

- Cement: 612 lb.
- Fine Aggregate: 1158 lb.
- Coarse Aggregate:
  - 2A: 1035 lb.
  - 3B: 1035 lb.

Air entraining cement was used, but no tests were made to determine actual air content. The water content was such that the slump was in the range of 1 - 2½ inches. The test cylinders cured with the test specimens were used to determine the compressive and tensile strengths at the end of one, two, three, and four days. The other six cylinders were used to determine the standard 28-day strengths. The strengths determined from the cylinder tests are given in Tables 1A and 1B.

The No. 5 deformed bar reinforcement was hard grade, ASTM designation A432-59T. Tensile tests were performed on three specimens in determining the yield point to be 72,500 psi. and the ultimate strength to be 102,500 psi. Three specimens of the D18.4 deformed wire were similarly tested. The yield strength at 0.2% was found to be 81,600 psi., and the ultimate strength to be 88,900 psi. Typical stress-strain relationships for the No. 5 bars and for the D18.4 deformed wire are shown in Figure 2.
2.2 Loading Apparatus

At each end of a specimen, the six No. 3 bars and the longitudinal reinforcement were anchored to a movable yoke. At one end, the yoke was attached to a large-diameter bar which, in turn, was attached to a fixed bulkhead. With SR-4 strain gages attached to the surface, the large diameter bar served as a load cell and enabled determination of the load in the specimen at the anchorage end. A view of the anchorage end is shown in Figure 3. At the other end of the specimen, an identical arrangement was used, except that the load cell bar was attached to the movable bulkhead which was used to induce the longitudinal strains. A view of the loading end is given in Figure 4.

2.3 Instrumentation

The total longitudinal strain in a specimen was measured with two Ames dials, each having a least count of 0.0001 inch. At each end of the specimen, one of the dials was used to measure the movement of a small steel bar vertically embedded in the specimen. A view of one of the dials in place is shown in Figure 5.

To aid in the detection of cracks and to measure crack widths, small brass plugs were embedded at 10-inch intervals in the top surface of the specimen. The incremental strains were measured with an extensometer having a least count of 0.0001 inch.

The longitudinal load resulting from the introduction of a prescribed strain was measured with the load cells described previously in Section 2.2.
2.4 **Testing Procedure**

After the concrete had aged twenty-four hours, the strain cycling was begun. During a given cycle, a strain was introduced in increments over a two-hour period. This strain was maintained for four hours, then released, again in increments over a two-hour period. The specimen was then left without restraint for 16 hours. By the prescribed test program, the first three cycles were spaced 24 hours apart. Then, since failure had not occurred in any of the specimens at the end of the three cycles, an ultimate load test was conducted when the age of the specimen was four days.

For the first cycle, the longitudinal strain represented a temperature drop of 35\(^\circ\). The coefficient of thermal expansion for the concrete was taken as 6.5 x 10\(^{-6}\)/\(\text{F}\). Since the range of this property extends from 3.2 to 7.0, a high value was chosen to represent a more severe condition. Just prior to the beginning of the second cycle, the length of the specimen was normally less than the length at the beginning of the first cycle. This was mainly due to the effect of shrinkage. Therefore, the strain induced during the second cycle was equivalent to that which would be produced by a 42\(^\circ\) drop in temperature, plus the amount required to bring the specimen back to its original length. The same procedure was followed in the third cycle. In all cases, the strain was applied and released in five approximately equal increments.

In the ultimate load test, the strain was induced in increments approximately equal to those used in the third cycle. The specimen was
loaded until either a bond failure resulted in fracture at the lap, or a fracture in the reinforcement resulted in failure in another region.
3. TEST RESULTS

3.1 Crack Formation

In general for all specimens, several cracks appeared during the first load cycle. New cracks formed during each of the following two cycles and during the ultimate load test. The prescribed failure criteria was based on the width of the crack pre-formed at the center of the lap. If this crack opened to 0.1 inch, then the specimen was considered as having failed. Actually, the pre-formed crack did not reach the failure limit in any of the specimens. In fact, the pre-formed crack did not even form in four of the specimens: A-2, A-3, A-4, and B-5. For each of the specimens the maximum crack widths during each of the load cycles are given in Table 2. For a more complete picture of the maximum strains or crack widths which occurred during each load cycle for each specimen, Figures 6, 7, 8, 9, 10, and 11 indicate values at each 10-inch interval along the length.

The behavior of all specimens was about the same in the overall formation of cracks. Views of the final crack pattern for each specimen are also given in Figures 6 through 11. It should be pointed out that in the region of the lap, there was definitely a greater tendency for cracks to form at the ends of the lapped reinforcement rather than at the section which was purposely weakened within the lap.
3.2 Ultimate Load Test

Series A: In specimens A-1 and A-2 (18-inch lap), two different types of failure occurred. In A-1, a bond failure developed in the lap region. However, in A-2, fracture of one of the bars occurred at a location approximately midway between the lap and the end where the jacks were located. The other bar was not fractured. In both specimens A-3 and A-4 (16-inch lap), the failure mode was the same - a bond failure in the lap region.

Series B: Two different types of failure occurred in the two Series B specimens (18-inch overlap). In B-1, failure occurred when all three longitudinal wires were fractured at a cross-section located approximately four feet from the jacking end. In B-2, a bond failure occurred in the lap region.

The failure loads are listed in Table 3 along with the force which was required to produce yield in the reinforcement. The maximum crack widths measured just prior to ultimate failure are listed in Table 2. A typical bond failure in the lap region is shown in Figure 12.
4. DISCUSSION AND CONCLUSION

The primary objective of this project was to evaluate the behavior of the slab specimens when subjected to longitudinal strains which, in general, produced the same effect as a drop in temperature would produce in an actual pavement slab. In particular, attention was centered on the behavior in the region of the lap splice of the main reinforcement. Three strain cycles were administered before loading the test specimens to ultimate failure, because it was felt that weaknesses which might be responsible for failure in a pavement slab would appear during the first three days after the concrete had been placed. All six of the test slabs successfully withstood the three strain cycles with no crack widths reaching the defined failure width of 0.1 inch. In the region of the lap, a crack formed at the thin plate in only two of the specimens. In general, the tendency seemed to be toward the formation of cracks at or near the ends of the lapped bars, rather than within the splice.

In the ultimate load tests the behavior appeared to be satisfactory in all cases. Even in the ultimate load tests, no crack in any Series A specimen opened to the failure width of 0.1 inch. In both of the Series B specimens, crack widths exceeded 0.1 inch during the last load increment before fracture occurred. With one exception, the load developed at failure was essentially equal to, or greater than, the load which would have produced yield in the main reinforcement. The one exception was in specimen A-3. It is felt that the lower ultimate load
was principally due to the relatively low strength of the concrete in this specimen, rather than to the length of overlap. The behavior of specimen A-4 substantiates this feeling. In the Series B specimens, the ultimate loads were actually in the vicinity of the load which would have produced fracture in the reinforcement. However, this is not surprising since the bond area was greater and the fracture load for the reinforcement was lower than for the Series A specimens.

It is felt that the results of these tests emphasize the adequacy of the 16-inch lap for the No. 5 bar reinforcement of the type used, and of the 18-inch lap for the D18.4 welded wire fabric used. It was not the purpose of these tests to determine the minimum lap length necessary, only to evaluate the lengths prescribed in the test program.
This project was performed at Lehigh University in the Department of Civil Engineering, headed by Prof. W. J. Eney. The laboratory work was conducted in the Fritz Engineering Laboratory. Dr. L. S. Beedle is the Director of the Laboratory. The project was directed by Dr. D. A. Van Horn, Research Associate Professor. The work was sponsored by the Pennsylvania Department of Highways and the U. S. Bureau of Public Roads. The committee responsible for outlining the program included C. D. Jensen and R. K. Shaffer of the P.D.H.; H. D. Cashell and J. W. Burdell, Jr., of the B.P.R.; and C. L. Hulsbos, I. J. Taylor, and D. A. Van Horn of Lehigh University.

R. G. Adams, Research Instructor, was in charge of the laboratory work. R. Feenan, A. Guilford, and R. Badaliance assisted with the testing operation. Thanks are due to members of the Laboratory Operations group for help in conducting the entire program, and to Mr. A. C. Weber of the Laclede Steel Co. for making available the deformed welded wire fabric.
Table 1. Concrete Strengths

A. Compressive Strengths

<table>
<thead>
<tr>
<th>Age, Days</th>
<th>Specimen</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
<th>A-4</th>
<th>B-1</th>
<th>B-2</th>
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<td></td>
<td></td>
<td>1420</td>
<td>2600</td>
<td>920</td>
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<td></td>
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</table>

B. Tensile Strengths (Splitting)

<table>
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<tr>
<th>Age, Days</th>
<th>Specimen</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
<th>A-4</th>
<th>B-1</th>
<th>B-2</th>
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Note: Values are in psi. - Each value represents the average of three tests.
Table 2. Ultimate Loads and Maximum Crack Widths

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Main Reinforcement</th>
<th>Length of Overlap, in.</th>
<th>Maximum Crack Width - inches</th>
<th>1st Day</th>
<th>2nd Day</th>
<th>3rd Day</th>
<th>4th Day Prior to Ultimate</th>
<th>Act. Failure Load, Kips</th>
<th>Load Producing Yield in Reinf., Kips</th>
<th>Type* of Failure</th>
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<tbody>
<tr>
<td>A-1</td>
<td>No. 5 Bars</td>
<td>18</td>
<td></td>
<td>0.019</td>
<td>0.021</td>
<td>0.021</td>
<td>0.059</td>
<td>44.4</td>
<td>45.0</td>
<td>B</td>
</tr>
<tr>
<td>A-2</td>
<td></td>
<td>18</td>
<td></td>
<td>0.032</td>
<td>0.029</td>
<td>0.028</td>
<td>0.045</td>
<td>45.4</td>
<td>45.0</td>
<td>F</td>
</tr>
<tr>
<td>A-3</td>
<td></td>
<td>16</td>
<td></td>
<td>0.017</td>
<td>0.022</td>
<td>0.025</td>
<td>0.032</td>
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<td>45.0</td>
<td>B</td>
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<tr>
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<td>16</td>
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<td>46.6</td>
<td>45.0</td>
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<tr>
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<td>Deformed WWF</td>
<td>18</td>
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<td>0.044</td>
<td>0.051</td>
<td>0.057</td>
<td>0*123</td>
<td>47.1</td>
<td>44.8</td>
<td>F</td>
</tr>
<tr>
<td>B-2</td>
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<td>0.052</td>
<td>0.144</td>
<td>45.6</td>
<td>44.8</td>
<td>B</td>
</tr>
</tbody>
</table>

* B - Bond failure at lap
  F - Fracture of reinforcement
Fig. 1 Details of Specimens
Fig. 2  Typical Stress-Strain Relationships for Main Reinforcement
Fig. 3 Anchorage End

Fig. 4 Loading End - Movable Bulkhead
Fig. 5  Typical Test Specimen
Fig. 6 Strains at Maximum Daily Loads - Specimen A-1
Fig. 7 Strains at Maximum Daily Loads - Specimen A-2
FIG. 8  Strains at Maximum Daily Loads - Specimen A-3

Side View of Crack Pattern at Ultimate Load

Gage Points

Failure Location

Lap Region

TOTAL STRAIN IN EACH 10 in. GAGE LENGTH (x 10^{-4} in.)

-100  100  200  300  400  500  600  700

Strain at 1st Day Max. Load

Strain at 2nd Day Max. Load

Strain at 3rd Day Max. Load

Strain at 4th Day Max. Load

Legend
Fig. 9 Strains at Maximum Daily Loads - Specimen A-4
Fig. 10 Strains at Maximum Daily Loads - Specimen B-1
LEGEND

- Strain at 1st Day Max. Load
- Strain at 2nd Day Max. Load
- Strain at 3rd Day Max. Load
- Strain at 4th Day Max. Load

Fig. 11 Strains at Maximum Daily Loads - Specimen B-2
Fig. 12 Typical Bond Failure - Lap Region