Railroad Research on Prestressed Concrete

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By **E. J. Ruble*** **and F. P. Drew****

Prestressed concrete is recognized in this country today as a material which can be used with confidence in the construction of railroad bridges. Ten years ago this was not so. At that time the railroad engineer had a choice between steel, timber or reinforced concrete. Now he can also consider the use of prestressed concrete.

Prestressed concrete had been used in Europe for many years; the first railroad bridge being erected in Belgium in 1942. It was first introduced in this country with the construction of the Walnut Lane Highway Bridge in Philadelphia in 1949. The use of prestressed concrete for bridges and buildings has grown steadily ever since. The first prestressed concrete railroad bridge was placed in service in 1954. This bridge is located near Hunnewell, Missouri on the Chicago, Burlington and Quincy Railroad.

Since the construction of these bridges it has been demonstrated in the field and in the laboratory that the principal advantage of prestressing is that it combines the high compressive strength of concrete with the high tensile strength of prestressing steel to produce an economical structural member.

That the railroads are taking advantage of this material is evidenced by the fact that at the present time there are 37 prestressed concrete railroad bridges in this country. These are well distributed geographically on 20 different railroads with a total of 285 spans. The majority of these are in the 20 ft. to 30 ft. range, but one bridge has 75 ft. spans. One large southeastern railroad has programmed the construction of a 1,100 ft. long bridge involving 24 ft. spans.

Bridges are not the only application the railroads are making of prestressed concrete. In 1960 the first prestressed concrete ties were installed on the Seaboard Air Line Railroad and on the Atlantic Coast Line. This was not the first time that concrete was used for track ties, but since earlier concrete ties had to be removed on account of corroded fastenings or deteriorated concrete it was thought that improvements in fastening details and concrete technology could be utilized to produce a tie with a long service life expectancy. At the present time there are about 30,000 prestressed concrete ties in service in this country. While this may be a relatively small proportion of the one billion timber ties in use it does demonstrate that prestressed concrete is well adapted for this application.

Prestressed concrete has also been used as the foundation for the rails where two tracks cross, for prestressed concrete piles, and of course,

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*Executive Research Engineer
Association of American Railroads
Chicago, Illinois

**Research Engineer, Structures
Association of American Railroads
Chicago, Illinois

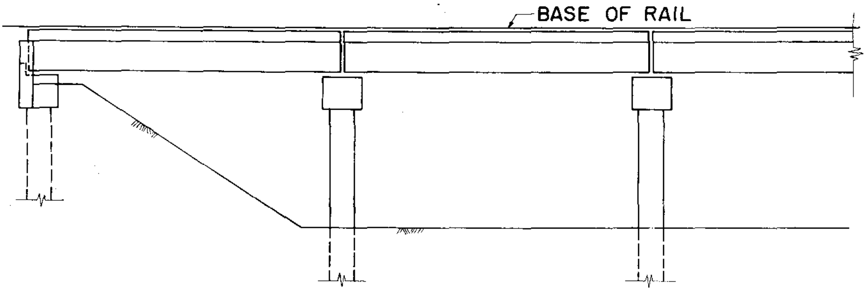

Fig. 1—Typical concrete slab span.

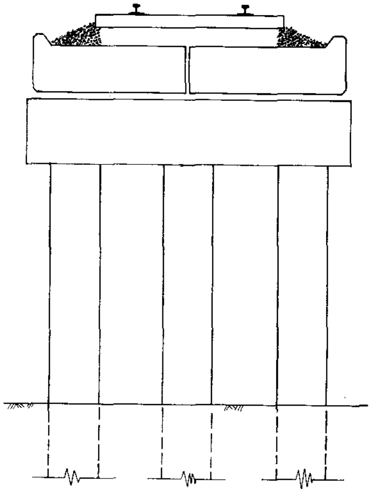

Fig. 1A—Cross section of typical concrete slab span shown in figure 1.

various railroad buildings have been built of this material.

Recognizing that prestressed concrete has a definite place in the railroad picture the American Railroad Engineering Association adopted in 1961, Specifications for Design, Materials and Construction of Prestressed Concrete Structures.

A current project of the Subcommittee on Prestressed Concrete of AREA Committee 8 is the design and preparation of detailed plans for a prestressed concrete trestle. The spans for this trestle will be 28 ft. long precast, prestressed hollow box girders. This length is a multiple of the 14 ft. bent spacing commonly used for timber trestles and was chosen to simplify the pile driving. Two widths of girders are proposed—3 ft. and 4 ft. with a depth of 2 ft. 9 in. The width and depth of girders was chosen intentionally to conform to standards of the American Association of State Highway Officials. This was done to provide standardization and to take advantage of existing plant set ups where highway spans have been cast.

When the Burlington Railroad placed the first prestressed concrete span in service, it did so with the assurance provided by a research program that the span would safely carry the expected service loading. This was the first of several research investigations conducted by the Association of American Railroads to provide its member roads with confidence in a new material. This research has been conducted in the laboratory on full-size bridge members—not models—under static and repeated loading and in the field on actual prestressed concrete bridge members under locomotive and car loadings. The results of these investigations need no interpretation or extrapolation for size effect. The results are direct and provide the bridge engineer with information he can readily understand and use.

A discussion of some of the laboratory investigations which the AAR

Fig. 2—Static testing of full size prestressed concrete slab span at the Bureau of Reclamation laboratory in Denver. Notice that loading is being applied off center to simulate field conditions.

has conducted with prestressed concrete follows. The complete reports of these investigations are published and only the highlights will be brought out here.

The first investigation conducted by the AAR was on a full-size slab. The slab span as shown on Fig. 1 has always been a popular type with the railroads principally because it can be erected in place with very little interruption of traffic. Once in place the bridge deck is complete and ready for ballast and ties and no additional concrete casting is required. For this investigation we took one-half of this deck, put it in a test machine of the Bureau of Reclamation in Denver and loaded it statically to its ultimate capacity. This view, Fig. 2, shows the slab in place. Notice that the load is applied off center. This was to simulate field conditions where the track loads are heaviest under the rails and least toward the outside edge.

The slab was 72 in. wide, 18 in. deep and 19 ft. long. It was designed for E72 plus full impact. Sixty-one ½ in. strands were used and stressed to an initial prestress of 0.75 ultimate or 180,000 psi. The concrete had attained a strength of 7,670 psi at the time the strands were cut and when the slab was tested the concrete strength was 9,300 psi.

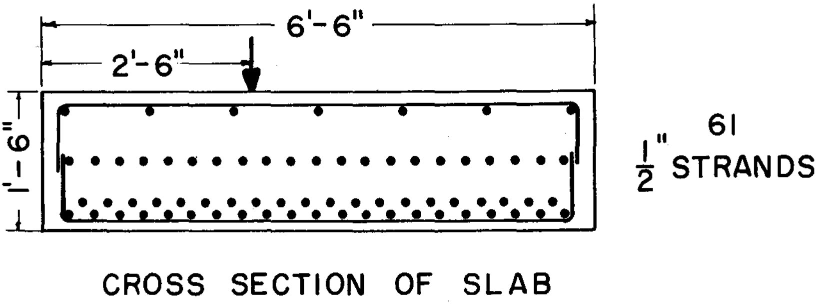

Fig. 2A—Cross section detail of the test slab shown in figure 2.

This investigation showed that:—

1. The entire prestress force was transferred to the concrete in a length of about 6 in.
2. The ultimate load was more than three times design load.
3. There were no shear cracks.
4. There was no bond failure even at ultimate load.
5. Failure was in concrete compression associated with plastic straining of the strands.

The performance of this slab gave the Burlington Railroad engineers sufficient evidence that similar slabs could be safely used in their bridge and in 1954 such slabs were installed as shown in Fig. 3. Each span consists of two slabs. The prestressed span which is only 18 in. deep is shown at the right and a regular reinforced concrete span, 24 in. deep is on the left.

Since these two spans, each of quite different design, were installed adjacently, an excellent opportunity was provided to compare the dynamic effects under identical loading conditions. A few of the more significant features of this investigation are:—

1. The maximum impact recorded in the regular design slabs was 30% and in the prestressed slabs was only 10% (Fig. 4).
2. The total impact recorded in the prestressed slab was only one-fifth the present AREA design impact allowance.
3. All recorded stresses were less than calculated.

It is interesting to note that the AREA impact allowance for the prestressed slab was 51% and for the regular design slab was 46%. This empirical impact equation which was established for steam locomotives is:

$$I = \frac{100L}{L + D}$$

where L is the live load and D is the dead load. It is apparent that as D increases, I will decrease. Hence, if impact is a function of the weight of the span, the recorded impacts in the heavier, regular design slab should have been less than those in the lighter prestressed slab. The opposite relationship was found. This study indicated that impact in concrete spans needs reviewing and that its basis should be that of actual field investigations as has been done for steel spans.

While the previous investigations provided valuable information on the static and dynamic properties of these slabs, it was recognized that their performance under repeated loading needed to be demonstrated. A program was set up at Lehigh University for this purpose.

Using the same depth of beam, the same percentage of steel and the same prestressed force as was used in the full-size bridge slabs, beams 16½ in. wide, as shown on Fig. 5, were made for the repeated load investigation. (If test machines of sufficient capacity were available the full width could have been used.) Concrete strength was one of the variables in this investigation. The concrete strength for each pair of beams was as follows: 8850, 7730 and 5750 psi. One static test and one repeated load test was con-

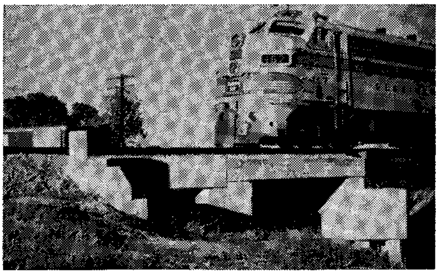

Fig. 3—C.B.&Q. RR Bridge 38.64 at Hunnewell, Missouri.

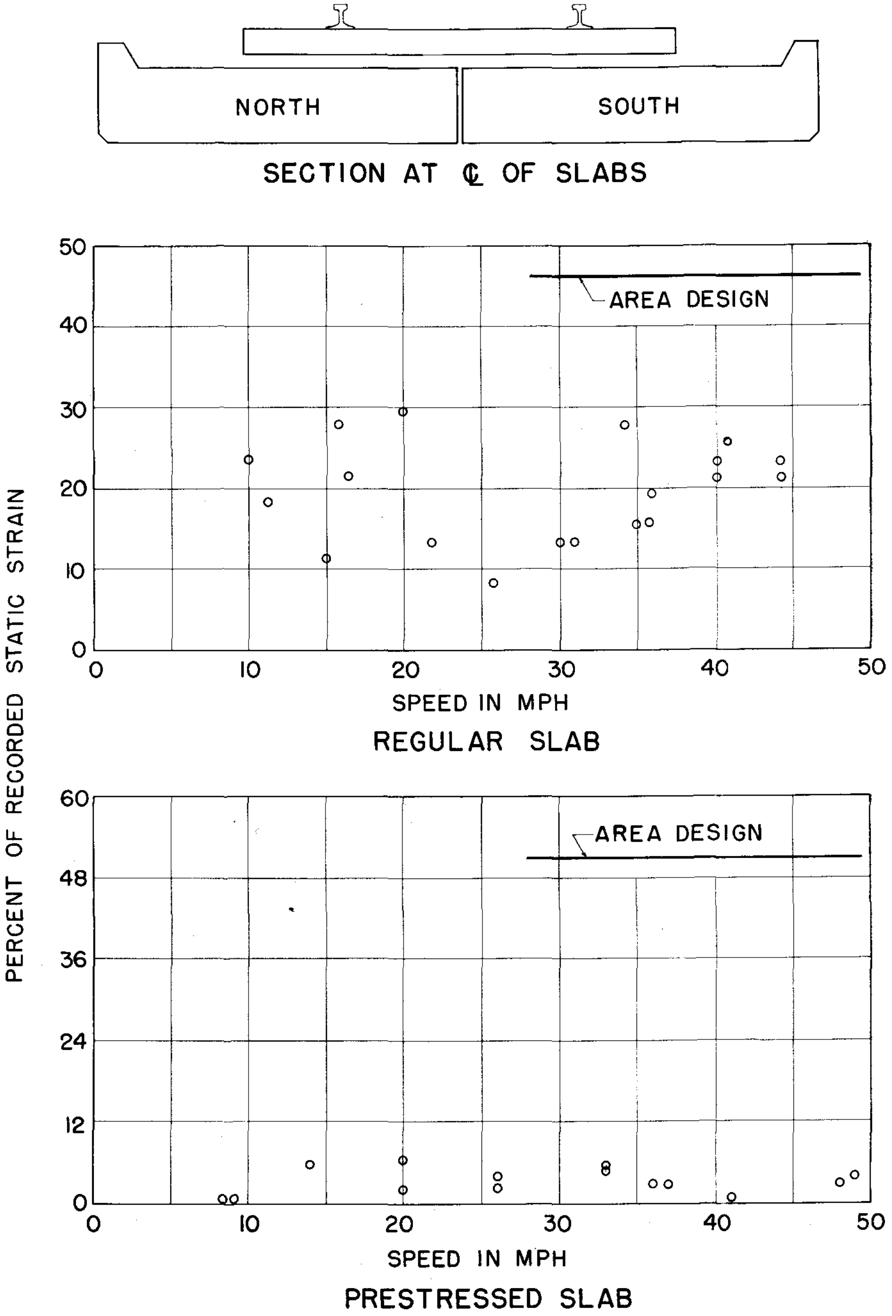

Fig. 4—Total impacts recorded in concrete of C.B.&Q. RR Bridge at Hunnewell, Missouri.

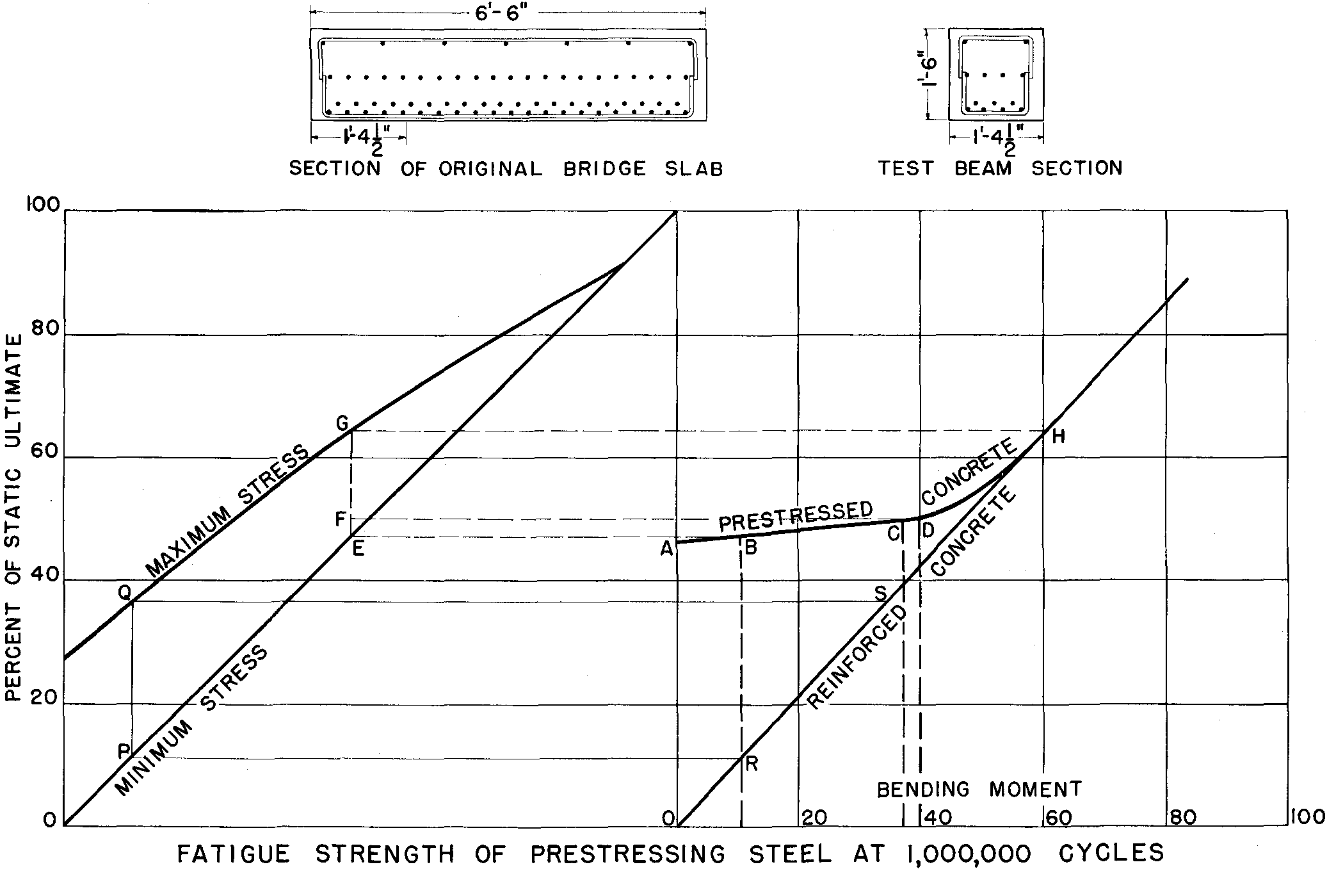

Fig. 5—Repetitive loading graph obtained from tests made at Lehigh University.

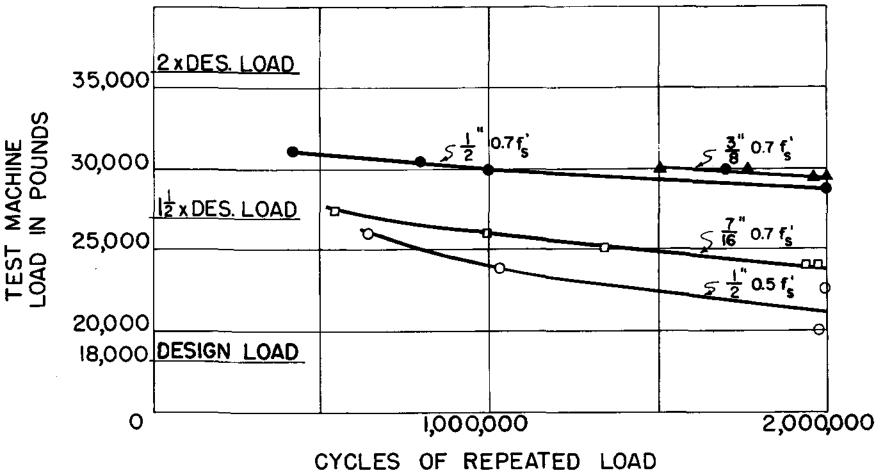

Fig. 6—Effect of size of strand and level of prestress on fatigue strength.

ducted for each concrete strength.

This investigation produced much more information than can be dealt with in the scope of this paper and we suggest you refer to the full report. However, these points are significant:

1. The theory of fatigue failure can be used for predicting repeated load strength.
2. Loads 1½ times design load will not cause failure at 1,000,000 cycles.
3. There was no strand slippage.
4. The 5750 psi concrete was sufficient for the repeated load investigation. Higher strength concrete was not advantageous.
5. Loaded statically, the beams failed in concrete compression. Under repeated loading they failed in the strands.

The theory of fatigue failure used in this study is worthy of further description particularly as to how a fatigue failure can be predicted.

The lower portion of Fig. 5 and the diagram to its' left is a modified Goodman-Johnson diagram for the prestressing strand used. The envelope between minimum and maximum stress indicates the range of stress which can be repeated 1,000,000 times without failure. It is apparent that as the minimum stress increases the range of stress must decrease. If the stress range for a given loading falls within this envelope, failure will not occur in 1,000,000 cycles. This is a convenient tool for the designer when repeated type loading is involved. It should be noted that the ordinates are given as percentages of the static ultimate strength of the strand.

At the right of this diagram is plotted the relationship between bending moment and strand stress for these beams. Point A is the effective prestress in the strands. B is the stress under dead load moment. C is the design load stress, D is the stress at cracking load. It should be noted at this point that the curve between A and D is a straight line at a very flat slope. It can be seen that if point B is projected to the left until it intersects the minimum stress line at E and if point D is also so projected, that point F lies well within the envelope and no fatigue failure will occur. However, if the bending moment is increased so the steel stress has a value at H (at this point flexural cracks have formed), it is seen that the projection of this point intersects the maximum stress curve at G and indicates that a further increase in stress or bending moment will cause fatigue failure at 1,000,000 cycles.

These diagrams point up the superiority of prestressed concrete over reinforced or non-prestressed concrete.

This can be easily demonstrated by extending a line from point H to the origin. This would be the condition for a beam reinforced with steel strand but without any initial pretension. It can readily be seen that the range of stress P-Q would permit a bending moment increase from dead load, R, to about design load, S. For the prestressed beam the moment can be increased 50% over design.

In the full report of this study these diagrams have been extended to show compressive stresses with an envelope for concrete. With such a combined diagram the designer can predict whether the beam will fail in the strand or in the concrete or whether it will fail at all.

In an extension of the work at Lehigh, the AAR conducted a laboratory investigation with similar beams to demonstrate the effect of size of strand and level of prestress on the repeated load strength of the beams.

Twenty-four beams were involved in this study and the results are shown on Fig. 6. As was the case with the Lehigh beams, static loading produced compressive failures and repeated loading produced tensile strain failures.

It can be seen by the diagram that beams with lower prestress had lower repeated load strength, although they were able to sustain loads 1¼ times design for 2,000,000 cycles. While the beams with ⅜ in. and ½ in. strands had about equal strength under repeated loads, those with 7/16 in. strands had somewhat less. The reason for this has not yet been determined and this program is still underway.

Soon after the prestressed slabs were installed at Hunnewell, the Southern Railway was making plans for two bridges which were to utilize hollow rectangular beams. Before these beams were to be used in a bridge, static tests were conducted to demonstrate their performance under loads to the ultimate.

Using loading equipment in the fabricating plant one of the beams was subjected to a static load to failure as shown on Fig. 7. This test indicated that:

1. The ultimate load was about three times the design load. Failure was in concrete compression.

2. Flexural cracks did not appear until 1¾ times the design load was applied.

3. The prestress force was transferred to the concrete in a length of about 18 in.

Beams of this design were installed in a bridge of the Southern Railroad near Dry Fork, Virginia. The AAR conducted a field investigation of this bridge in 1958. The test was made with diesel locomotives operating at speeds up to 87 mph. The following significant information was obtained from this test:

1. All recorded stresses were less than calculated.

2. The maximum recorded impact

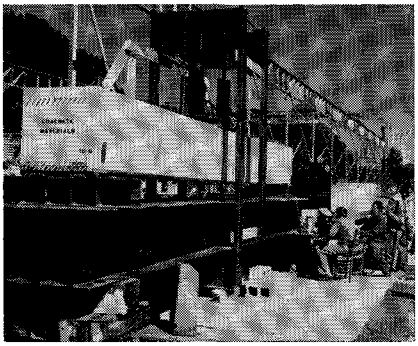

Fig. 7—Determining static strength of a prestressed concrete beam.

was 32% which was 60% of the AREA design impact allowance.

3. The transverse distribution of load to the six beams under the track indicated that only the four beams under the ties carried significant load.

As shown in Fig. 8 the curb beam and the beam near center line between tracks carried negligible load. No transverse post-tensioning or shear keys were used. The design assumption was thus verified that only four beams carried the live load.

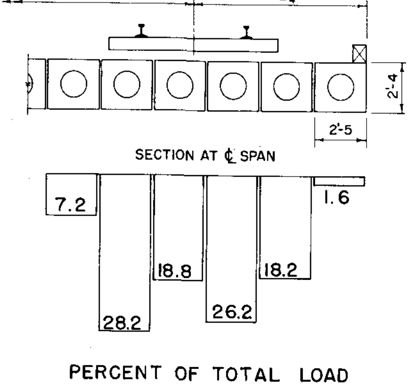

Fig. 8—Transverse distribution, Southern RY. Bridge, Dryfork, Va.

A similar bridge was constructed by the Florida East Coast Railway near Pompano Beach, Fla. as shown in Fig. 9. A field investigation was conducted on this bridge and while static and dynamic effects were observed the most interesting information obtained was related to the effect of shear keys and transverse post-tensioning on the distribution of live load to the beams.

One of the spans had been constructed with shear keys but the others had been left plain. Using the shear key span and one other as test spans, simultaneous strain readings were taken in each of the six beams under a test train. The transverse post-tensioning was then applied and another set of readings taken with the same train.

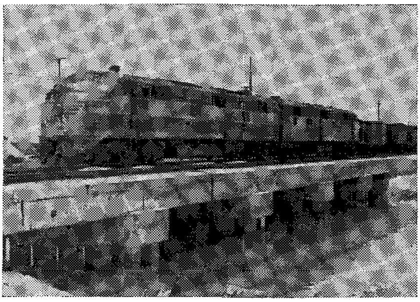

Fig. 9—Florida East Coast Ry. Co. Bridge 334.93, Pompano Beach, Fla.

Fig. 10 shows the distribution on the span with shear keys before and after post-tensioning. It can be seen that the shear keys are effective and that post-tensioning does little to further improve the distribution.

Fig. 11 shows the distribution without shear keys before and after post-tensioning. It is very apparent that the post-tensioning improved the distribution considerably in this instance.

A conclusion of this investigation was that either shear keys or transverse post-tensioning is effective in

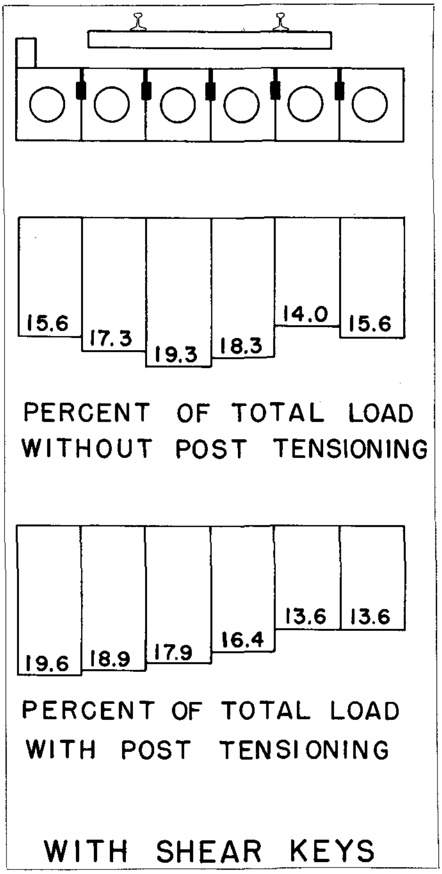

Fig. 10—Transverse distribution with shear keys, F.E.C. Ry. Co., Pompano Beach, Fla.

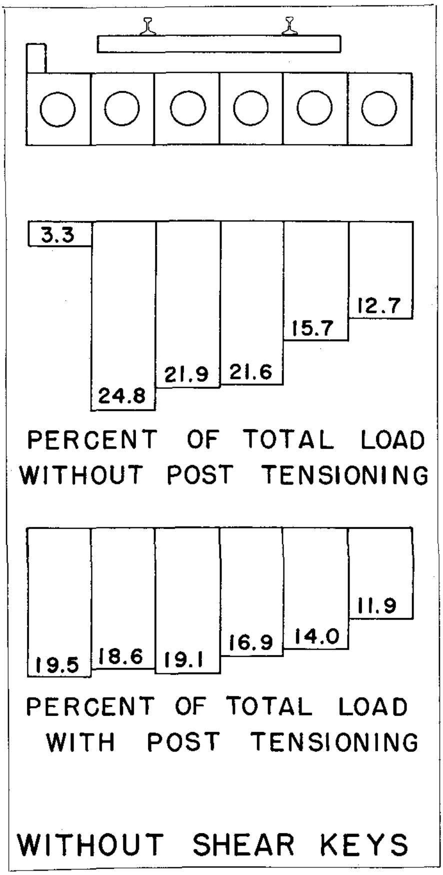

Fig. 11—Transverse distribution without shear keys, F.E.C. Ry. Co., Pompano Beach, Fla.

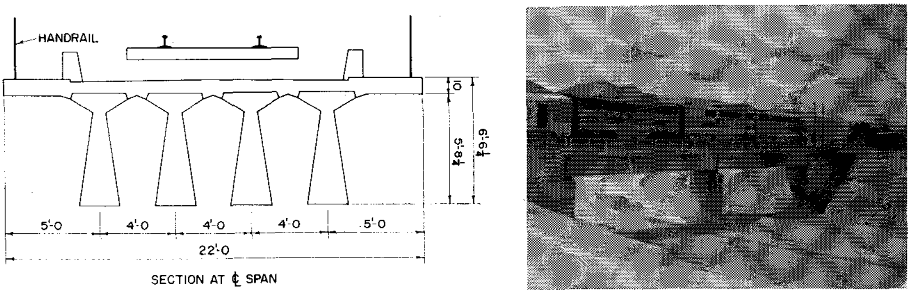

Fig. 12—Photo and detail of A.T.S.F. Ry. Bridge 672.1, Colorado Springs, Colo.

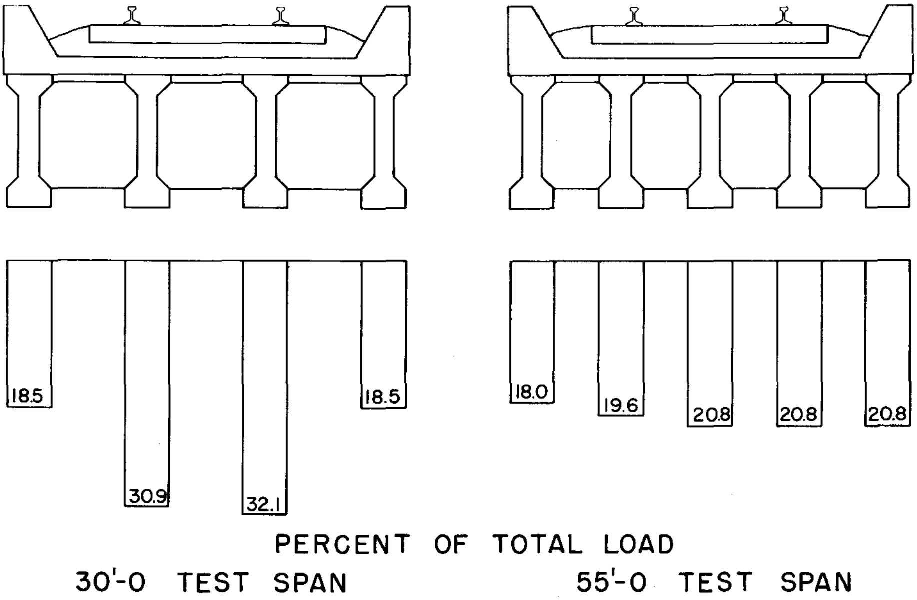

Fig. 13—Transverse load distribution to prestressed concrete girders, Southern Pacific Co., Houston, Texas.

distributing the load across the deck. Using both together does not improve the distribution, but transverse rods may be helpful during erection for drawing the beams together and to prevent spreading later under service. If shear keys are used such rods need not be tightened to a high tension, nor do they need to be of high strength steel. Past practice has been to place the transverse rods through the mid-height of the beams, however, it would seem that such rods would be more effective if placed at the lower third point of the beam depth. The proposed AREA specification for box beams will show this arrangement together with shear keys.

Fig. 14—Southern Pacific Co. Bridge 0.46 at Houston, Texas.

AREA design impact for these beams for the diesel locomotives used was 44%. The maximum recorded under a locomotive was 38%, but most values were 20% or less.

All the field investigations mentioned so far have been of the rectangular slab or box type. Other types have been used by the railroads such as shown in Fig. 12 of the Santa Fe bridge near Colorado Springs, Colo. These girders are 71 ft. 6 in. long cast and post tensioned on the site and erected in position. The slab and curbs were cast in place. Obviously this type of construction requires a shoo-fly or runaround track.

The measurement of strains under static and dynamic loading indicated that:

1. Load distribution to each girder was approximately equal.
2. Whereas the AREA impact allowance for this span was 34% the recorded impact was only 13%.
3. The vertical strain distribution indicated composite action between the curb and the slab and between the slab and the girders.

A field investigation was conducted on another similar type bridge of the Southern Pacific Company, Texas and Louisiana Lines. Two spans were tested in this study —one 30 ft. and one 55 ft. Their cross sections are shown on Fig. 13.

Curves on the approaches restricted the speed of trains over this bridge so impact on the spans could not be determined. Static effects were measured, however, and as shown on Fig. 13 the load distribution to the girders in each span was determined. It can be seen that for the span with five girders per track, the distribution to each was nearly equal while for the case with four girders per track the girders directly below the ties carry a greater share of the load. The cast in place slab and curbs were found to be acting composite with the girders. Fig. 14 shows the completed bridge.

More field investigations are needed to provide adequate data upon which to base an impact equation. However, from the information on hand at present, it appears that the present AREA impact equation is too conservative and that prestressed concrete spans can safely be designed with less impact.

So far we have discussed laboratory and field investigations of railroad bridge members. We have also conducted extensive investigations of prestressed concrete cross ties.

In 1957, the AAR research staff decided that even though the supply of wood ties was ample at the present and for the foreseeable future, some prestressed concrete ties should be designed, manufactured, laboratory tested and a few installed on several railroads to secure service performance over a period of years in case our timber supply or economic conditions changed.

The first ties were designed on the basis that one prestressed concrete tie would replace one wood tie at the same spacing. Static and repeated load tests indicated that such ties were satisfactory but by increasing the width of the tie to 12 in. and increasing the tie spacing to 30 in. there would be only a 10% increase in rail stresses and no increase in bearing pressure on the ballast. Such a tie was designed and is shown on Fig. 15.

The principle design features of

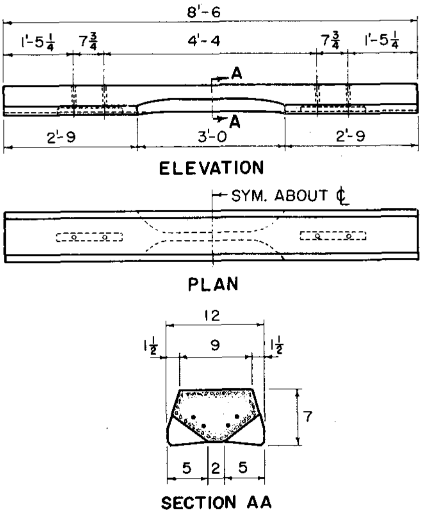

Fig. 15—Association of American Railroads Prestressed Concrete Tie Design E.

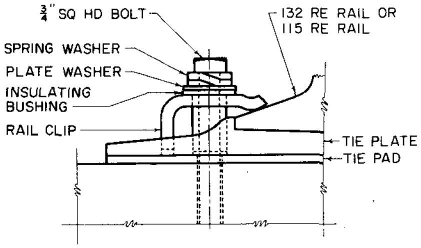

Fig. 16—Association of American Railroads Rail Fastening Assembly.

this tie are:

1. The concave base under the rail to help retain the ballast.
2. The wedge shaped center section to reduce the bearing of the tie on the ballast and eliminate center binding.
3. The heavy steel clips (Fig. 16) to provide positive rail anchorage and eliminate rail anchors.
4. The increased weight of the tie and the positive anchors provide greater lateral stability for welded rail.

The laboratory phase of this investigation consisted of static and repeated loading of ties under simulated end-bound and center-bound conditions, repeated loading of ties in ballast, repeated loading of the rail fastenings, tie plates and pads and torque pull-out tests of anchors.

While these laboratory studies were aimed at developing a tie and fastening that would be expected to give good service in main line track, for the final analysis actual in-place service would offer the best demonstration of performance. Accordingly, two test installations were made in 1960 one on the Seaboard Air Line near Tampa, Florida where 600 ties were placed and the other on the Atlantic Coast Line near Four Oaks, North Carolina with 500 ties. Both of these installations representing about ¼ mile of tangent track, were in high speed territory and both installations are under continuous welded rail.

The installations offered an opportunity to determine that regular track laying equipment that has previously been used with timber ties can be used with the concrete tie. Service performance is, of course, the primary objective of these test installations.

Several of these ties were instrumented for the purpose of obtaining oscillograph recordings under actual train operations.

Information was obtained such as:

1. Top and bottom concrete strains.
2. Bending moment.
3. Distribution of wheel loads.
4. Effect of tie pads on impact.
5. Effect of various bolt tensions on tie and fastening behavior.

Many relationships were established in this study but one which was very significant was that the recorded bending moments were very close to that used in the design calculations namely 150,000 in. lbs. under the rail. However, maximum moments of 190,000 in. lbs. were recorded for short durations of time. Since concrete can withstand considerably higher stresses under extremely short time loading this excess moment is not considered detrimental.

Since the ties were installed several inspections have been made. General performance seems to be good. Some cracking has been noted, but it is felt that this can be remedied by slight revision in the design.

Current research on prestressed concrete at the AAR is concerned with the static and repeated load strength of full-size box girders designed in accordance with the proposed AREA specification. It is particularly significant that this is a

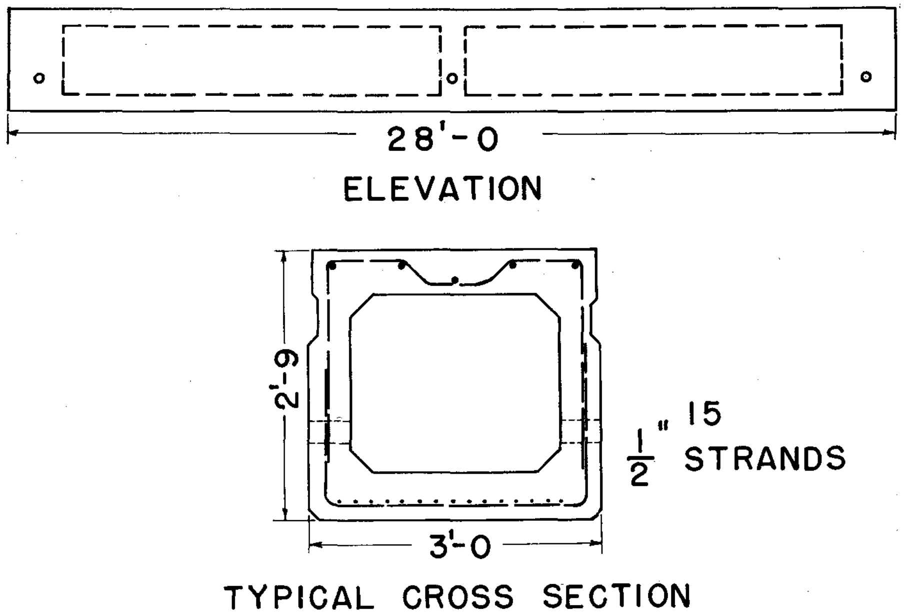

Fig. 17—Standard AREA Box Girder.

cooperative project of the Prestressed Concrete Institute and the AAR. The PCI has furnished the girders and laboratory investigation is being conducted by the AAR.

The girders shown in Fig. 17 are being proposed for inclusion in the AREA Manual as standard construction for prestressed concrete trestles.

Four girders are included in this investigation—one for static loading and three for repeated loading. The static loading test has been made. The ultimate moment was three times the design moment. The first tensile crack appeared at a load of 1⅔ times design load. Deflection at ultimate was nearly 3½ in.

An extension of this investigation is planned to include similar girders fabricated with light weight aggregate.

Prestressed concrete can hardly be considered a new and untried material anymore. Railroad research and usage have shown that this material offers advantages heretofore unrealized. Continued research and development will permit prestressed concrete to take its place among the more versatile construction materials.

References

1. Investigation of Full-Size Reinforced Concrete Railway Bridge Slabs. AREA Proceedings, Vol. 59, 1958, p. 133.
2. Static and Fatigue Tests on Prestressed Concrete Railway Slabs. AREA Proceedings, Vol. 60, 1959, p. 1.
3. Investigation of Southern Railway Prestressed Concrete Beams. AREA Proceedings, Vol. 62, 1961, p. 59.
4. Field Investigation of Santa Fe Railway Prestressed Concrete Girders. AAR Research Center Report ER-18, 1961.
5. Prestressed Concrete Tie Investigation. AAR Research Center Report ER-20, 1961.
6. Field Investigation of Florida East Coast Prestressed Concrete Beams. AAR Research Center Report ER-21, 1962.
7. Field Investigation of Southern Pacific Company, Texas and Louisiana Lines, Prestressed Concrete Girder Spans. AAR Research Center Report ER-25, 1962.