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# Final report: development and refinement of load distribution provisions for prestressed concrete beam-slab bridges, November 1980.

David A. VanHorn

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Project 72-4: Development and Refinement of  
Load Distribution Provisions for  
Prestressed Concrete Beam-Slab Bridges

FINAL REPORT

FRITZ ENGINEERING  
LABORATORY LIBRARY

by

David A. VanHorn

Prepared in cooperation with the Pennsylvania Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Pennsylvania Department of Transportation, the U.S. Department of Transportation, Federal Highway Administration, or the Reinforced Concrete Research Council. This report does not constitute a standard, specification, or regulation.

LEHIGH UNIVERSITY

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Fritz Engineering Laboratory Report No. 387.5

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ABSTRACT

This is the final report on the research investigation entitled "Development and Refinement of Load Distribution Provisions for Prestressed Concrete Beam-Slab Bridges" (PennDOT 72-4). The report includes (1) the main body of the original research proposal, (2) the results from the project, as set forth in the five reports nos. 387.1, 387.2A, 387.2B, 387.3, and 387.4, and (3) a summary relating the results to the objectives of the project.

## I. Introduction

This is the final report on PennDOT Project No. 72-4: "Development and Refinement of Load Distribution Provisions for Prestressed Concrete Beam-Slab Bridges". This report contains the main body of the proposal (Section II); results of the investigation, as set forth in the abstracts of the five reports developed in meeting the objectives of the project (Section III); and a summary (Section IV) relating the objectives of the project to the results set forth in the reports, along with some personal comments of the writer relative to implementation of the results and to future research.

## II. The Proposal

### A. ABSTRACT

Field studies of eight in-service beam-slab type prestressed concrete highway bridges in Pennsylvania have indicated the need to develop new specification provisions in the general area of live-load distribution. Work completed to date has resulted in a proposed new specification for right (no skew) bridges of the spread box-beam type. The objectives of the proposed work are (1) to develop a similar new specification for prestressed concrete I-beam superstructures, (2) to develop new provisions to cover the effects of skew in both the I-beam and spread box-beam types, and (3) to investigate the possibility of developing provisions which cover the effects of interior-span diaphragms, curb-parapet sections, and continuous-span construction.

### B. PROBLEM STATEMENT

The proposed research investigation is in the area of design of highway bridge superstructures. Specifically, the primary intent is: (1) to develop a new method for the evaluation of live-load distribution factors for beam-slab type highway bridges basically consisting of a reinforced concrete deck slab supported longitudinally by prestressed concrete I-beams, and (2) to extend the coverage to include the effects of skew for both the I-beam and spread box-beam types. The Penn-dot has been, and is currently, involved in directly related work through sponsorship of the following projects at Lehigh University:

- 64- 6: Lateral Distribution of Load for Bridges Constructed with Prestressed Concrete Box-Beams;
- 67-12: Lateral Distribution of Load for Bridges Constructed with Prestressed Concrete I-Beams; and
- 68-27: Structural Response of Prestressed Concrete Box-Beam Bridges.

## C. BACKGROUND AND SIGNIFICANCE OF WORK

### 1. Literature Review:

First of all, it would be appropriate to draw attention to the 15 project reports which have been completed on projects 64-6,<sup>1-8</sup> 67-12,<sup>11-15</sup> and 68-27,<sup>9-10</sup>. (References are listed on pages 10 & 11.) These reports contain detailed information on the structural behavior of eight in-service prestressed concrete beam-slab highway bridges subjected to static, dynamic, and impact loading through use of a test vehicle which closely simulated an HS 20-44 design vehicle. Six of the test bridges were of the spread box-beam type, and two were of the I-beam type. The report which describes the development of the proposed specification for spread box-beam bridges, along with the accompanying mathematical analysis, is F.L. Report 315.9<sup>7</sup>. Four of the reports<sup>12-15</sup> are devoted to results from the field investigations of the two I-beam bridges, and form the basis for the eventual comparison with results from the proposed mathematical analysis.

A major literature review was undertaken at the start of project 67.12, and is presented in F.L. Report 349.1<sup>11</sup>. Over the past three years, additional information has been added to yield an extensive bibliography on the subject of load distribution in beam-slab bridges.

### 2. Significance of Work:

Research completed to date on Projects 64-6, 67-12, and 68-27 has clearly indicated the need for revision of the current specification provisions for live-load distribution in prestressed concrete beam-slab superstructures. The mathematical analysis presented in Report No. 315.9, solidly reinforced with the quantitative results from field test and small-scale model structures, has been utilized to develop a suggested new specification provision for both interior and exterior beams in the spread box-beam superstructure. The new provision was developed

from an analysis of superstructures consisting of the slab, beams, and end diaphragms. The effects of the curb and parapet sections, and of the midspan diaphragms, were completely excluded in developing a provision which (1) reflects the current design philosophy of ignoring the stiffening and strengthening effects of the curb and parapet sections, and (2) ignores the nearly negligible effect of widely spaced diaphragms on the distribution of live loads. Currently a proposal is being formulated for presentation to the AASHTO Committee on Bridges and Structures, in support of adoption of the new provision by the AASHTO. (This provision now appears in the AASHTO Standard Specifications for Highway Bridges: Art. 1.6.24[A].)

For the I-beam superstructures, field tests of two in-service bridges have been completed and four reports have been developed. The results from these tests (1) indicate the need for new provisions which parallel those already developed for the spread box-beam bridges, and (2) provide an excellent data base for comparison with the results from the mathematical analysis which forms the backbone of the proposed investigation.

Although it is felt that the proposed provision for spread box-beam bridges represents a significant improvement in the specifications covering load distribution, it is significant that neither the current nor the proposed specifications for any type of beam-slab construction include provisions which cover the effects of skew, or of interior-span diaphragms or spacers. In addition, no guidance is provided for assessing the effects of curb-parapet sections and continuous-span construction.

### 3. Method of Solution:

In the past, a variety of methods have been developed for the analysis of beam-slab bridge superstructures. However, in each case, a number of limitations or simplifying

assumptions were made in order to overcome the mathematical difficulties involved in each of the solution procedures. In seeking the extensive information included in the proposed work, the adoption of an accurate, efficient solution technique is required. The conventional approaches used in past studies are simply inadequate for the proposed work. Therefore, a relatively new technique will be used, the Finite Element Method. This method has already had extensive application in aeronautical and naval engineering, and during the past decade, the use in Civil Engineering has been gradually intensified.

Basically, the Finite Element Method is a discretization technique which replaces an infinite degree of freedom system by one with finite degrees. The entire structure is discretized into a finite number of regions (elements) interconnected at certain points (nodal points). In the proposed work, the bridge superstructure will be broken down into plate, beam, and other elements to represent the behavior of the slab, beams, diaphragms, and other structural elements. In the displacement-type formulation (stiffness method), the stiffness matrix for each element is derived. The global stiffness matrix for the entire bridge superstructure is obtained by the direct stiffness method, which will be based on elemental stiffness matrices. This matrix, along with the given displacement boundary conditions and loads, is solved for displacements. Insertion of the displacements into predefined matrical expressions will then yield the various stress conditions in the plates and beams.

Right (no skew) bridges will be analyzed by using beam finite elements and rectangular plate elements. Parallelogram-shaped plate elements, instead of rectangular elements, will be employed in the skewed bridge investigation. To prevent the duplication of effort, all previously developed algorithms and techniques will be utilized. Past experience has shown

that the investigation can be undertaken and successfully completed by the proposed research team.

D. OBJECTIVES:

The primary objectives of the proposed investigation are:

1. To develop a new provision for live-load distribution in prestressed concrete I-beam bridge superstructures, paralleling the currently proposed provision for spread box-beam bridges.
2. To expand the already-completed live-load distribution provisions for the spread box-beam bridges, and the provisions for the I-beam bridges proposed above in objective No. 1, to include provisions for inclusion of the effects of skew.
3. To investigate the possibility of extending the analysis and specification development to cover: (a) the effects of interior-span diaphragms, (b) the effects of curb-parapet sections, and (c) continuous-span construction.

E. IMPLEMENTATION OF RESULTS:

The results from this research program will be utilized in developing design recommendations and specification provisions in the general area of live-load distribution in beam-slab highway bridge superstructures of the prestressed concrete I-beam and spread box-beam types. Specifically, the developments will include a new expression to yield live-load distribution factors for the I-beam type; a method to modify the live-load distribution factors for both the I-beam and spread box-beam types to account for the effects of skew; and possibly, methods to assess the effects of interior diaphragms, the effects of curb-parapet sections, and modifications needed for application to continuous-span construction.

In the implementation of these results, the several recommendations will be presented in the interim and final reports. After review by representatives of the Bridge Division of the PennDOT, the final version of the recommendations would be presented to the AASHTO Committee on Bridges and Superstructures, in a process which would hopefully lead to adoption by the AASHTO.

F. BENEFITS

The specification development resulting from the proposed investigation will yield a more accurate and more extensive method for assessing the distribution of live loads in the design of highway bridges. This refinement of the design process will, in many cases, result in a reduction in construction costs, and will, in all cases, result in a more accurate evaluation of live-load effects in the superstructure. The direct beneficiary at the PennDOT would be the Bridge Division; however, the eventual adoption of the new specification by the AASHTO would yield benefits to bridge designers throughout the United States. Obviously, the ultimate benefit would be to the public, primarily through the probable reduction in construction costs.

G. PROPOSAL AND RESEARCH PLAN

It is proposed that a research program be initiated with the objectives listed in Section D, and with the following procedure:

1. The first step in the procedure will be the completion of the literature search, already begun as described in Section C.1. In addition, a summary of the results from the three projects already completed (see Section B) will be included, with delineation of both specific and general recommendations for possible implementation.

2. The next step in the procedure will be the development of the analysis and the computerization of the mathematical method. Next, the two field-test structures will be investigated analytically, under the field test loading conditions. The results from the analysis will then be compared with the field test results, and any necessary changes or refinements will be incorporated into the analysis.

After the analysis has been completed, the following parameters will be systematically varied in series of computer runs to establish both qualitative and quantitative effects on various aspects of structural behavior: beam spacing, span length, beam size, bending and torsional stiffness of the beams, slab thickness, roadway width, number of traffic lanes, skew, and relative stiffness of beam and slab concretes. The study will include different bridge configurations and different loading conditions. The HS 20-44 design load vehicle, with concentrated wheel loads, will be placed in various traffic lanes and at different locations to produce critical design conditions corresponding to the different loading arrangements. The equivalent HS 20-44 lane loading will also be considered for comparison purposes. The solution technique will be general enough to enable consideration of other vehicular loadings. Attention will be focused on the standard beam cross-sections (AASHTO-PCI Types I-VI, and PennDOT standard sections). The study of skew will be extended to superstructures of the spread box-beam type.

After all design parameters have been included in the variation process, the factors which prove to have a significant effect on the load distribution will be incorporated into mathematical equations or charts. The intent will be to provide accurate information in a form which is acceptable to design engineers. In this regard, it is probable that the development of the specification for the I-beam bridges

will closely parallel the earlier development for box-beam bridges, as presented in F.L. Report 315.9<sup>7</sup>. However, it should also be emphasized that additional factors may be included in the proposed I-beam specification, depending on the results from the analysis. In any case, strong emphasis will be placed on the preparation of workable specification provisions.

3. Following completion of the previously described work, a pilot study will be conducted to determine the feasibility of extending the analysis and specification development to include provisions for the assessment of the effects of interior-span diaphragms, curb-parapet sections, and continuous-span construction.

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F.L. Report 349.4, October 1971

### III. The Results

Report No. 387.1: STRUCTURAL BEHAVIOR OF BEAM-SLAB HIGHWAY BRIDGES -- A SUMMARY OF COMPLETED RESEARCH AND BIBLIOGRAPHY

Abstract: This is the first report on the research investigation entitled "Development and Refinement of Load Distribution Provisions for Prestressed Concrete Beam-Slab Bridges" (PennDOT 72-4). Included are (1) a review of the four recently completed Lehigh University research programs on the structural response of prestressed concrete beam-slab highway bridges of the spread box-beam and I-beam types, (2) a discussion of the general findings in these programs, and (3) an up-to-date annotated bibliography containing references which are directly or indirectly applicable to the structural behavior, analysis, and design of beam-slab type highway bridge superstructures.

Report No. 387.2A: LATERAL DISTRIBUTION OF LIVE LOAD IN PRESTRESSED CONCRETE I-BEAM BRIDGES

Abstract: This is the second report on the research investigation entitled "Development and Refinement of Load Distribution Provisions for Prestressed Concrete Beam-Slab Bridges" (PennDOT 72-4). The beam-slab bridges included in this study are of the I-beam type. Included are (1) a structural analysis, based on the finite element method, which describes superstructure response to design-vehicle loading, (2) a comparison of the structural analysis with results from the field tests of two in-service bridge superstructures, (3) the analysis of 219 superstructures ranging in length from 30 ft. to 135 ft., and in roadway width from 20 ft. to 78 ft., and (4) equations for evaluating live-load distribution factors for interior and exterior beams, based on the definition of traffic lanes set forth in the AASHTO "Standard Specifications for Highway Bridges - 1973" (1.2.6 - Traffic Lanes).

Report No. 387.2B: LIVE-LOAD DISTRIBUTION FACTORS FOR PRE-STRESSED CONCRETE I-BEAM BRIDGES

Abstract: This is the third report on the research investigation entitled "Development and Refinement of Load Distribution Provisions for Prestressed Concrete Beam-Slab Bridges" (PennDOT 72-4). The beam-slab bridges included in this study are of the I-beam type. Included are: (1) a structural analysis, based on the finite element method, which describes superstructure response to design-vehicle loading, (2) a comparison of the structural analysis with results from the field tests of two in-service bridge superstructures, (3) the analysis of 150 superstructures ranging in length from 30 ft. to 135 ft. and in roadway width from 24 ft. to 72 ft., and (4) equations for evaluating live-load distribution factors for interior and exterior beams, based on the definition of traffic lanes set forth in the AASHTO "Interim Specifications - Bridges: 1974".

Report No. 387.3: LIVE-LOAD DISTRIBUTION IN SKEWED PRESTRESSED CONCRETE I-BEAM AND SPREAD BOX-BEAM BRIDGES

Abstract: This is the fourth report on the research investigation entitled "Development and Refinement of Load Distribution Provisions for Prestressed Concrete Beam-Slab Bridges" (PennDOT 72-4). The effects of skew on the design moments and on the lateral distribution of statically applied vehicular loads are examined for prestressed concrete I-beam and prestressed concrete spread box-beam bridge superstructures. The finite element method is utilized to analyze 120 I-beam superstructures and 72 box-beam superstructures ranging in length from 34 ft. to 128 ft. and in roadway width from 24 ft. to 72 ft. Skew effects are correlated for bridges of different widths, span

lengths, number of beams, and number of design lanes, and empirical expressions are developed to facilitate computation of lateral load distribution factors for interior and exterior beams. The proposed skew distribution factors are actually based upon appropriate modifications to the distribution factors for right bridges. In general, the skew correction factor reduces the distribution factor for interior beams and increases the distribution factor for exterior beams. The magnitude of the skew effect is primarily a function of skew angle and of bridge span and beam spacing.

Report No. 387.4: A PILOT STUDY OF FACTORS AFFECTING LIVE-LOAD DISTRIBUTION IN PRESTRESSED CONCRETE BEAM-SLAB BRIDGES

Abstract: This is the fifth report on the research investigation entitled "Development and Refinement of Load Distribution Provisions for Prestressed Concrete Beam-Slab Bridges" (PennDOT 72-4). This report describes a very brief pilot study of the structural behavior of prestressed concrete beam-slab bridges, particularly live-load distribution, as affected by (1) curb-parapet sections, (2) intra-span diaphragms, and (3) continuity over the supports in multi-span structures.

For simple span bridges, it was found that consideration of the longitudinal strength and stiffness of the curb-parapet sections yields higher values of the live-load distribution factors for exterior beams and lower values for interior beams, when compared with distribution factors based on analyses which ignore the effects of the curb-parapet sections. The effect of intra-span diaphragms is to more evenly distribute the live load to the individual longitudinal beams. A diaphragm at midspan was found to be more effective than other combinations considered. For multi-span bridges

constructed with longitudinal continuity over the supports, the live-load distribution was found to be similar to the distribution in simple span bridges of shorter span.

#### IV. Summary

In this summary, reference will be made to the three objectives of the project, as set forth in Section II-D, and to the results set forth in the abstracts of the five reports listed in Section III.

The first step in the research program was the development of an up-to-date annotated bibliography of references applicable to the structural behavior, analysis, and design of beam-slab type highway bridge superstructures. This bibliography was presented in Report No. 387.1 which also included (1) a review of the four previous Lehigh University research programs on the structural response of prestressed concrete beam-slab highway bridges of the spread box-beam and I-beam types, and (2) a discussion of the general findings in these previous programs. This report represented the first step in the research program, as set forth in Section II-G.

The next phase in the program involved the development of a new provision for live-load distribution in prestressed concrete I-beam superstructures, paralleling the previously developed provision for spread box-beam bridges, which now appears as Article 1.6.24(A) of the AASHTO Standard Specifications for Highway Bridges. Report No. 387.2A presented a proposed new provision. This new provision was based on the definition of traffic lanes specified in Article 1.2.6 of the 1973 AASHTO Specifications. Upon completion of the analytical work which formed the basis for Report No. 387.2A, the AASHTO adopted a revision of Article 1.2.6, which first appeared in the 1974 AASHTO Interim Specifications - Bridges. Therefore, additional funding was provided to cover the development of a second new provision for live-load distribution in prestressed concrete I-beam bridge superstructures, using the 1974 definition of traffic lanes. The development of the second (new) provision was set forth in Report No. 387.2B.

Upon completion and approval of Report No. 387.2B, the proposed new specification revision was scheduled for presentation at the four regional meetings of the AASHTO Subcommittee on Bridges and Structures held in San Diego, Tulsa, Raleigh, N.C., and Durham, N.H., in the period April-May 1977. It is significant to note that the timing associated with the completion and approval of Report No. 387.2B enabled distribution to the State bridge engineers only one month prior to the regional meetings. Subsequently, the proposed new specification revision was presented by D. A. VanHorn at the four regional meetings. In all of the meetings, the proposal was favorably received. However, since there had been insufficient time for the State bridge engineers to review the report prior to the 1977 regional meetings, the proposal was referred to the Subcommittee on Load Distribution (of the AASHTO Subcommittee) for subsequent review and action at the regional meetings in 1978. The proposed new specification revision appeared on the agenda of the 1978 regional meetings. However, no one from Lehigh University or PennDOT was requested to attend the meetings to present further information, to answer questions, or to recommend approval. Consequently, there was little or no discussion of the proposed revision. As a result, the bridge engineers decided to stay with the current specification provisions.

The next step in the research program was to develop provisions which would cover the effect of skew on the already-completed live-load distribution provisions for both the I-beam bridges and the spread box-beam bridges. The required analysis was completed, and new provisions were developed, as set forth in Report No. 387.3. These provisions have not been presented to the AASHTO Subcommittee on Bridges and Structures.

Reports Nos. 387.2A, 387.2B, and 387.3 fulfill objectives Nos. 1 and 2, as set forth in Section II-D, and paragraph No. 2 under Section II-G.

Finally, a pilot study was conducted to provide an initial qualitative assessment of the effects of interior-span diaphragms, curb-parapet sections, and continuous-span construction, on live-load distribution in prestressed concrete beam-slab bridges. The results of the pilot study are presented in Report No. 387.4. This report fulfills objective No. 3 in Section II-D, and paragraph No. 3 under Section II-G.

In conclusion, it is the feeling of the writer (D. A. VanHorn) that it was unfortunate that the AASHTO failed to adopt the proposed new specification for live-load distribution in prestressed concrete I-beam beam-slab highway bridges, as set forth in Report No. 387.2B. The proposed new specification was clearly an improvement over the current specifications for live-load distribution in bridges of this type. More generally, it is the writer's feeling that the proposed specification could well serve as a model (in form) for the revision of all of the provisions currently included in Article 1.3.1 of the AASHTO Standard Specifications for Highway Bridges. Separate provisions (in the proposed form) are already included in the specifications for beam-slab bridges supported by steel box girders (Article 1.7.49(B)), and by prestressed concrete spread box-beams (Article 1.6.24(A)). Finally, it is the feeling of the writer that a future research program should be devoted to an overall revision of Article 1.3.1, and related articles, covering distribution of live-loads in beam-slab bridges.

## V. Acknowledgements

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