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Overloading behavior of beam-slab type highway bridges, Final Report Project 71-12, July 1977.

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16. Abstract

The report presents the summary of the research program on the prediction of the overload response of simple span beam-slab highway bridges with reinforced concrete deck and prestressed concrete I-beams. The analytical developments and numerical comparisons pertaining to the investigation were presented in the previous interim technical reports of the research project. This report presents the highlights of the observations made in different phases of the research. Recommendations and conclusions based on the overall research program have been enumerated with appropriate referencing to the detailed description of the relevant program area and technical reports. Any in-depth study of the research program summarized in the report requires close scrutiny of the interim reports of the project.

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COMMONWEALTH OF PENNSYLVANIA

Department of Transportation

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Project 71-12: Overloading Behavior of Beam-Slab
Type Highway Bridges

F I N A L   R E P O R T

OVERLOADING BEHAVIOR OF

BEAM-SLAB TYPE HIGHWAY BRIDGES

FRITZ ENGINEERING
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by

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LEHIGH UNIVERSITY

Office of Research

Bethlehem, Pennsylvania

July, 1977

Fritz Engineering Laboratory Report No. 378B.8

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ABSTRACT

This report presents the summary of the research program

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area.

Any in-depth study of the research program summarized in the

report requires close scrutiny of the interim reports of the project.

1. INTRODUCTION

Most bridges are occasionally loaded beyond the load levels for which they were designed. The overloading of bridge superstructures can occur (1) due to the transport of heavy industrial, construction or farm equipment, (2) due to the legal, across-the-board raise in vehicular weight limits, and (3) due to additional permit overloads. Another source of overloading, that tends to be overlooked as far as the possible response of the bridge is concerned, is the traverse of vehicles with a limited axle spacing and a limited number of wheels as compared to the design vehicle. The total weight of the vehicle may or may not be less then the total weight of the design vehicle, but the load is applied over a smaller area then that assumed by the designer. And finally, if the bridge to be traversed has deteriorated and lost some of its strength, even the original design vehicle can be considered as an overload vehicle for the superstructure.

The observations by the district bridge engineers in Pennsylvania and the forecasts made by various investigators have indicated that the overloading of highway bridges occurs frequently (e.g. Refs. 8,12,13,54,55). It is prudent to assume that the frequency of overloading will increase. Furthermore, a recent across-the-board increase of allowable truck weights changed vehicles that used to be considered as overloaded to legally loaded vehicles. It is also expected that similar legal increases in truck weight may again take place in the not to

distant future. The legalization of higher load levels, if not accompanied by appropriate programs to rate and strengthen the existing bridges, will cause all the bridges to be "overloaded" when subjected to this truck traffic. It has also been recognized that a substantial percentage of the existing bridges is in need of repair and rehabilitation; especially the bridge deck slabs. Through the loss of strength of the deck slab it is possible that the deterioration of these bridges is being accelerated when they are subjected to design vehicular loading, let alone vehicles that are in excess of the design vehicle (Ref. 21, 56,58).

The loading configurations considered in the design of superstructures in other countries are more severe than those employed in the United States and, more specifically, in the Commonwealth of Pennsylvania (Refs. 1,2,38,46,51,52,53,57). The frequency of overloading in some of these countries is not as great as that in the United States (Ref. 38). Consequently, the problem that is being confronted, and which will present even greater problems in the future, is the reduction in the reserve strength of the bridge superstructure and/or its components. This reserve strength, which is due to the conservative dimensioning of the structure, has taken care of the adverse effects of possible design inaccuracies, construction oversights, and limited deterioration of the superstructure. A diminishing reserve strength margin, however, will make the adverse effects of the sources listed above critical, thereby possibly requiring major bridge rehabilitation programs.

1.1 Objectives of the Reported Research

Studies have indicated that the current practice of computing the load that will be carried for different components of the bridge is not as realistic as it should be (Refs. 1,2,5,14,49,51,53). The simplest form of this is the computation of the lateral live load distribution factor. The behavior of the bridge superstructure assumed by the designer versus the actual behavior as can be observed in the field are different. This problem is further compounded when the superstructure is subjected to overload vehicles of various sizes and shapes. The AASHTO Overload Provisions may be used for some slight and infrequent overloading, due to the lack of any other method. However, when the overload vehicle has an uncommon weight and axle configuration there exists no reliable tool to predict the possible effects of the vehicle on the superstructure. This phenomenon has led the Overload Permit Officers to issue or deny the permit based more on their intuition than the results of the application of scientifically proven methods.

The first objective of the reported research was to develop a computer based analysis tool which could simulate the response of the bridge superstructure from dead weight load level up to the vehicular load level that would induce the collapse of the superstructure. It was also required to provide information for various load levels between zero live load and collapse load. Furthermore, it was imperative to define the load level which would induce the damage, recoverable or not, to the superstructure, the type and location of the damage, and its spread for increased load levels (Ref. 13).

The second objective of the research was to define service-ability characteristics of the bridge superstructure, based on the assessment of the damage due to the overloading, and to predict the ultimate load carrying capacity. During the conduct of the research additional tasks have been added, which are covered in Chapter 2. One of these tasks, the conduct of a parametric investigation on the over-load response of a limited number of bridges subjected to a limited number of overload configurations, should be considered as a primary objective. This phase of the research was to provide information on the overload behavior of the bridges that are built following current design practices.

The research was to be carried out for simple span beam-slab highway bridges without skew, consisting of reinforced concrete deck slab and prestressed concrete I-beams.

1.2 Scope of the Report

The conducted research is highly analytical and sophisticated. Any attempt to summarize the theoretical aspects will distract from the thrust of this report. This report is intended (1) to provide a guide to the interim research reports that have been issued as the require-ments of the project, (2) to provide a list of the publications related to the different phases of the reported research (the work leading to these reports was conducted outside the reported research and thus the researcher was not contractually required to issue them as interim reports), (3) to summarize the highlights of the findings included in

the interim reports that may be of interest to the practicing engineer, and (4) to make recommendations with respect to the general area of overloading.

1.3 Chronological Perspective of the Research

The research on the overloading of highway bridges was started by the author in 1968 on an unsponsored pilot investigation basis. In response to the author's proposal to the National Science Foundation for the initiation of a research project on the Overloading Behavior of Beam-Slab Type Highway Bridges, funding was provided for a two and a half year period starting in Fall 1970 (Grant No. GK-23589). A similar proposal, after incorporation of a number of revisions, was accepted by the Pennsylvania Department of Transportation (Ref. 13). The funding was provided by the Pennsylvania Department of Transportation (PennDOT), and by the Federal Highway Administration, U.S. Department of Transportation starting on October 1, 1971 (Pennsylvania Department of Transportation Research Project 71-12). Prior to the initiation of this funding approximately four man-years of research on overloading of highway bridges had already been invested. The duration of the research program was defined as two and a half years, however, during the conduct of the research various additional problem areas, which were not included in the original proposal (Ref. 13) were investigated at the request of the sponsoring agencies. The additional funding and time were provided to permit the investigation of these tributary problem areas.

In addition to this report PennDOT Research Project 71-12 required eight interim reports. These reports contain all the technical developments and findings of the research program. Even though the different phases of the research are expounded in Chapter 2 of this report, for the sake of quick referencing the interim reports are listed below:

1. Interim Report #1 reported the research on overloading of highway bridge beams (Ref. 24).

2. Interim Report #2 described, in the form of a user's manual, the use of Program BEAM, the computer program developed for the overloading analysis of reinforced and prestressed concrete I-beams (Ref. 25). The analytical developments for this program were presented in Interim Report #1 (Ref. 24).

3. Interim Report #3 presented the analytical developments to predict the overload response of reinforced concrete bridge deck slabs (Ref. 40).

4. Interim Report #4 presented the results of the pilot research on the shear punching susceptibility of bridge decks due to overloading (Ref. 20).

5. Interim Report #5 presented in detail the analysis scheme, and the appropriate comparisons, to predict the overload response of bridge superstructures (Ref. 43). This phase of the research corresponds to the fulfillment of the primary objective of the research, that is, the development of an analysis scheme to predict the overload response of highway

bridges.

6. Interim Report #6 is the detailed user's manual for Computer
   Program BOVA (Bridge OVerload Analysis) (Ref. 42). BOVA is
   based on the analytical developments reported in Interim
   Report #5 (Ref. 43).

7. Interim Report #7 contains the listing of Program BOVA (Ref. 44).
   The version that is listed in the report is the one that is
   operational at Lehigh University Computing Center's CDC 6400
   Computer. This report is aimed only at individuals who are
   charged with the maintenance of the program. The generation
   of a deck from this listed version by punching the cards would
   be a futile attempt. The program contains about 13,000 cards
   and any mis-punching can lead to gross errors which can
   easily go undetected.

8. Interim Report #8 presents the results of the parametric inves-
   tigation on the overloading of highway bridges (Ref. 18).
   The results are tabulated in Overload Directories for each
   case. The report is aimed at the practicing engineer and per-
   mit officers.

   In addition to the above, two other activities that have taken
place in the research program have been transmitted to the Pennsylvania
Department of Transportation in the form of "letter to file," or technical
letters. These are:

1. Prediction of the possible damage to a bridge due to the
   envisioned transfer of nuclear reactor components over it
   (Ref. 14).

2. The analytical prediction of the overload response of the "Penn State Test Track Bridge" and the interaction with PennDOT Research Project 71-8, An Experimental Prestressed Concrete Bridge (Ref. 19).

Finally, to expedite the use of Program BOVA input data sheets have been prepared and transmitted to the sponsoring agencies.

1.4 General Observations on Overloading and Existing Bridges

An attempt has been made in the previous sections to define the sources of overloading and their possible adverse effects on the bridge superstructures. The bridge engineers, who have been charged with the maintenance of the structural integrity of the superstructures, have long been cognizant of the overloaded vehicles encountered in the traffic streams and the possible adverse effects of these vehicles on the bridges. However, since the inception of the reported research program, and especially during the last few years, a far greater awareness by the media of the rather deteriorated state of some of the bridges and the safety aspects involved have come into attention. Due to the budgetary constraints under which the Departments of Transportation have to operate, the solution to the existing situation requires long range planning and substantial investments in the rehabilitation of the bridge superstructures and the regulation of the traffic streams that may contain overloaded vehicles and underrated bridges.

There are four specific issues that need to be considered for better appreciation of the problem area:

1. Overloaded vehicles in the traffic arteries

2. Regulation of the overloaded vehicles and permit operations

3. State of deterioration of the superstructures

4. Rehabilitation and retrofitting of the existing bridges that have deteriorated.

1.4.1 Overloaded Vehicles

Over the years there have been some traffic counts undertaken at certain "checkpoints" in major traffic arteries that also included determining the gross weight and the axle weights of these vehicles. The attempts usually did not include the defition of the width of the axles and the number of wheels per axle. Thus, the information is not as complete as it should be (Ref. 18). Furthermore, no fully integrated approach has been undertaken to collate and correlate the different recordings undertaken in different states, e.g. Pennsylvania, Maryland, Texas, etc.

As an illustration of the distribution of the vehicular weight the summary paper by Heins and Derucher can be considered (Ref. 55). The paper incorporates the measurements by various researchers at various locations and suggests new "vehicular configurations" for possible usage in the fatigue study of steel bridges. If the vehicles they have grouped are compared to the "H" and "HS" series standard design vehicles of AASHTO (Ref. 55 vs. 53) it can be noted that, even though both the gross mean vehicular and axle weights are less than that of AASHTO, the maximums are notably in excess of the design provisions. It is realized that

(1) one-to-one comparison of the vehicles cited in the paper (Ref. 55) and the AASHTO Standard Specifications for Highway Bridges is not possible due to the differences in axle configurations, and (2) some of the vehicles given in Ref. 55 are not applicable to bridges on the interstate highway network system. It nevertheless clearly indicates the existence of overload vehicles that are more frequent than the "infrequency" that AASHTO Specifications refer to for overloading. From an overloading standpoint, even though the results are for steel highway bridges, observations can safely be extended to prestressed concrete bridges to illustrate the magnitude of the problem. The average stress, as reported by the authors, is about 1 ksi. This confirms the belief of most of the bridge designers that the bridges are understressed. About 50% of the time the stresses are 1 ksi or less. However, according to the stress histogram for a very small percentage there are stress recordings up to 6 ksi; in other words there are more than infrequent occasions that the stresses in the bridge components are beyond the very low stresses referred to above. It should also be noted that this study (Ref. 53) did not report any local or total failures due to overloading.

A pilot study undertaken by Lehigh University, sponsored by the Pennsylvania Department of Transportation (Research Project 75-17), used an existing bridge as a weighing device for the vehicles. During the weighing process the presence of the weighing operations were not widely publicized in order to obtain unbiased

data, i.e. prevention of the redirection of the heavy vehicles to alternate routes (Ref. 54). The truck count included 1,227 samples, which corresponds to a larger data base as compared to the previously cited summary study (Ref. 53). The study for five-axle vehicles has indicated that the legal weights are exceeded at least as follows:

Steering plus drive axles	1.6%
Trailer axles	6.0%
Individual axles	25.2%
Gross vehicle weight	20.8%

If the axle or the gross vehicular weight is taken as a benchmark for the overloading it can be stated that one out of every five trucks with five axles is above the "legal limits." Because of the pilot nature of this study the listed percentages may be questioned to some extent. However, even if it was assumed that one out of every ten vehicles exceeds the legal limits, the overall situation clearly conflicts with the term of "infrequency" cited in the overloading provisions of the AASHTO Standard Bridge Specifications (Ref. 53).

Furthermore, again in the above referred study, it has been reported that the following maximum axle and gross weights were recorded:

Combination	Recorded Weight (kips)	Legal Weight (kips)
Steering plus drive axle	90	58.4
Trailer axle weight	70	36

Individual axle weight	45	18
Gross vehicle weight	125	73.28

These weights are indirectly computed from strain gages, thus permitting the use of the bridge as a weighing station. The results that are obtained through the deflection gages attached to the superstructure also follow a similar pattern of loading (Ref. 54).

From these two studies it can be concluded that
(1) The bridges are loaded beyond the load levels for which they were designed. The frequency of the overloading is more than "infrequent"; about 20% of the time for 5-axle vehicles.
(2) The extreme values of the overloading can be far in excess of the design load levels, as much as twice the legal limits according to field measurements (Ref. 54). However, the frequency of this extreme loading is usually less than a few percent, 1-3% on the average, of the five axle truck traffic.

1.4.2 Regulation of Overloading of Vehicles

Recently the Commonwealth of Pennsylvania enacted Regulations Governing the Movement of Oversize and Overweight Loads and Vehicles (Ref. 57). The Regulation defined "overweight" and "super load" as they pertain to overloading. The maximum axle loads as well as the gross vehicular weights along with the various number of truck tractor axles and number of semitrailer axles have been defined. The author believes that these regulations are quite

helpful, however, they are far from being realistic due to the
following:

1. A very heavy vehicle can safely traverse the bridge if
    the number of wheels per axle are sufficient and the
    axles are arranged such that the gross weight is uniformly
    spread over a large area. A configuration as such may not
    cause adverse effects to the superstructure (Ref. 18),
    whereas, for example, a lighter vehicle with a limited
    number of wheels and axles, and with short axle and wheel
    spacing, may produce much higher stresses (Ref. 18). The
    revision of the aforementioned Regulation is advisable,
    in due course, as more information becomes available on
    the effects of various overload configurations to bridge
    superstructures.

2. For bridges whose structural integrity can not be fully
    ascertained the vehicles defined in the Regulation can
    easily correspond to a highly undesirable loading config-
    uration. Thus, as far as the interpretation and the
    implementation of the Regulations are concerned, a great
    amount of responsibility rests with the permit officer
    and especially the bridge engineer.

3. Similarly, the "Recommended Policy on Maximum Dimensions
    and Weights of Motor Vehicles to be Operated Over the
    Highways of the United States" by AASHTO (Ref. 52) is
    essentially based on the "Overload Provision (Section
    1.2.4 of Ref. 53). Depending upon the combination of

geometry of the bridge superstructure versus overloading

configuration the recommendations contained in this

reference may or may not lead to a reliable benchmark

criterion, as has been illustrated through case studies

in Reference 18.

Under the circumstances it can be safely stated that the

existing regulations and recommendations governing the overloading

are useful tools in the absence of any other means. They are some-

what more realistic than the reverse design process, i.e. using

lateral load distribution factors to determine the possible over-

stressing of the bridge beams (Ref. 14). This corresponds to a

highly unconservative approach since it has been found that the most

critical component of the bridge superstructure is the deck slab

(Ref. 18). The current guidelines also are not based on the slab

behavior (Refs. 52,53,57).

1.4.3 Deterioration of the Bridge Superstructures

Bridge superstructures, just like any other manufactured

system, have a finite service life. The duration of the service

life of bridge superstructures can rapidly shorten if they are not

continually maintained and repaired. The structural maintenance

and repair program corresponds to continual financial investments

for the bridge superstructures. Due to severe financial constraints

many of the rehabilitation projects for the superstructures have not

been properly administered. It has been accepted both by the bridge

engineers and the layperson alike that approximately 20% of the bridges in the United States are either functionally obsolete or structurally deficient (Refs. 56,58). The adverse effects of the bridge deck deterioration on the overload response of the super-structures have already been illustrated in Reference 18.

Bridges that were once designed for certain design load levels and configurations can now be considered as overloaded under the same loading if the superstructure has deteriorated sufficiently (Ref. 21). The rating of these bridges is then required. Consequently, the problem of overloading is not, and should not be, strictly linked to the vehicles, but should be linked to the bridge and vehicle simultaneously.

1.4.4 Rehabilitation of Existing Bridges

As has been publicly acknowledged, a large number of existing bridge superstructures must be repaired and retrofitted to bring them up to acceptable standards. Recent legal increases in permissible vehicular weights have led to the ambiguity in the definition of the actual load carrying capacity of the superstruc-ture. In view of the overloads noted, as explained in Section 1.4.1, and bridge deterioration, as explained in Section 1.4.3, the problem that is being faced is far more widespread than anticipated.

In regard to the rehabilitation of the bridges, there have been many moves and suggestions (Ref. 56). Irrespective of the amount of funds that can be allocated, if at all, for the

rehabilitation of the bridges, it will take a long period of time to accomplish this task, during which time the bridges that have been considered as acceptable will then require rehabilitation programs.

The temptation to further increase the vehicular weights, due to economic advantages, will further compound the problem.

Therefore, the problems that were cited in the original proposal of this research project have, unfortunately, become more critical than they were when stated in the proposal in 1971 (Ref. 13). It is prudent to assume that the severity of the problem will increase, unless drastic corrective measures are taken.

2. SUMMARY AND OBSERVATIONS

A literature survey indicated that there existed very little information on the overloading of highway bridges (Refs. 13,49,50,51). Analysis schemes to predict the overload behavior of bridges from zero live load level up to the collapse of the bridge did not exist. Field experience with bridges, specifically their testing to destruction, was too limited to draw any conclusions. The failure of bridges, due to one reason or another, was not widely reported because of its possible controversial nature. These limitations required a fully compartmentalized type of research program. That is, the total research was broken down into ingredients as simple as possible, and the investigations were conducted unit-by-unit. During the conduct of these compartmentalized research activities every effort was put forth to find reported laboratory and field test results to assess the accuracy of the developed methodology and make changes for each unit, if needed. This prevented the possible introduction of errors that would have had canceling effects in some cases and amplifying effects in some others, and would have resulted in an unreliable end-product. As each research unit proved its reliability it was interfaced with the others as the overall program dictated.

2.1 Introduction

The fundamental assumptions made at the beginning with respect to the analysis scheme have proven to be correct and of great importance.

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The assumptions are:

1. Bridge superstructures are too complicated to permit simpli-
    fication, i.e. treating the beams and deck slab separately.
    An approach as such is convenient for design purposes, how-
    ever, in predicting the true behavior of the superstructure
    it is imperative to consider the superstructure as a single
    entity. This has resulted in the use of finite element
    method for the analysis. The method required the simulation
    of the superstructure as an interconnected assembly of plate
    bending elements, for the deck slab, and beam elements, for
    the beams, as shown in Fig. 1. Other methods would have
    been either too crude or too cumbersome for this purpose
    (Ref. 13).

2. Neither the elastic analysis nor ultimate strength type
    analysis will reveal any useful information for the over-
    load response of the superstructure. Because of the inherent
    material nonlinearities in concrete, and to a lesser extent
    reinforcing bars and prestressing strands, even under the
    dead loads, at least parts of the superstructure exhibit
    nonlinear behavior. This will be further amplified as the
    damage to the superstructure initiates and spreads. The
    vehicular weight corresponding to the collapse load, as
    employed in conjunction with the ultimate strength analysis,
    is too high to be of any practical value. Furthermore, an
    approach as such will not reveal any information about the

type of local damage, its origin, load level at which it initiates, the pattern of its spread throughout the super- structure and the corresponding load levels. This had necessitated the adoption of a "load histogram" type approach in which the state of the superstructure would be predicted in detail for gradually increasing load levels for a given vehicle and for a given vehicular positioning.

3. As has been noted in some publications, the governing criteria for the bridge are not its ultimate strength but its "allow- able damage" and "serviceability limits" (Ref. 39). Any over- load permit operation based on approximate increases in allow- able stresses for a given vehicle can be misleading, as has been specified by AASHTO (Refs. 1,2,53), if the stress levels in the superstructure can not be correctly assessed. The exist- ing bridges already may contain some imperfections or damage (Ref. 3,7,21). Any simplifications in the analysis scheme without taking these damages into account may lead to a con- servative result at best, and to a grossly unconservative result at worst, leading to an unpredictable state as far as the possible effects of the overload vehicle on the superstructure.

4. If serviceability criteria are to be used and if a limited amount of damage to the superstructure is to be permitted for the overload permit operations, rating methods such as BRASS (Ref. 11), based on elastic analysis, should not be used.

In view of the above arguments, none of the existing and commonly used practical methods had any potential for usage within the reported research, not even with some modifications. This has been the primary reason for developing an analysis scheme based on fundamental assumptions and then testing the validity of each assumption, referred to above as compartmentalization of the research.

2.2 Sensitivity of the Superstructure to Approximations

A rigorous analysis scheme was developed to predict the elastic response of bridge superstructures. Comparisons with the available test data were made to verify the accuracy of the method and the approximations involved (Refs. 15,49). Different design parameters were varied one at a time to assess their effect on the overall stress and deformation patterns in the superstructure. This limited parametric study was undertaken to identify the design variables that need to be simulated with high precision and those that can tolerate errors (Refs. 5,48,49). The variables considered are too numerous to list, however, a partial list would include: span length, beam spacing, moment of inertia of the beams (sensitive parameters), modulus of elasticity and Poisson's ratio of the slab and beam concrete, eccentricity of the beam with respect to the slab, torsional stiffness of the beams, midspan diaphragms (less sensitive parameters).

The analytical formulations and the computer programs developed in this phase of the research permitted the proposition and initiation of Pennsylvania Department of Transportation Research Project 72-4,

Development and Refinement of Load Distribution Provisions for Pre-stressed Concrete Beam-Slab Bridges. Making full use of the experience and computer programs already developed, the new research project by-passed the developmental phase and was given a two year head start.

This phase of the research was supported in part by the National Science Foundation.

2.3 An Overloading Case Study

Prior to the development of any analysis scheme for the pre-diction of the overload response of bridge superstructures the researcher had undertaken a case study in response to a Pennsylvania Department of Transportation suggestion. At this phase of the research reliable elastic analysis procedures and pertinent computer programs were on hand. The investigation consisted of determining the possible effects of an overload vehicle traversing a bridge in Montgomery County, Penn-sylvania. The bridge had a span length of 89 ft. (c/c bearings), an out-to-out width of 45½ ft., and 6 prestressed concrete I-beams with a spacing of 7 ft.-10 in. The skew of the bridge was 77° 42' 11".

The overload vehicle consisted of a truck with one front and two driving axles and a trailer with three dollies. The single front dolly was attached to the truck, the rear of the vehicle had two dollies. Each dolly had three axles, and each axle had eight wheels. The total weight of the vehicle was reported to be 498,390 pounds. The maximum load applied by one of the dollies was 157,685 pounds. The

maximum axle weight was 40,175 pounds. The preliminary analysis of the bridge, conducted elsewhere, had indicated, by using AASHTO provisions, that there might be slight overstressing of the beams. Rigorous finite element analysis of the superstructure indicated that the critical component of the superstructure was not the beams, but the deck slab. This is due to the fact that while the beams immediately under the load will undergo large deflections, the beams that are not under the load will try to remain in their "unloaded" position. The deck slab will undergo large deformations in order to maintain the compatability of the deformations, i.e. pulling up the "loaded" beams and pushing down the "unloaded" ones. The traverse of the vehicle would have caused damage to the deck slab (Ref. 14). This finding, which has been confirmed in many instances during later parts of the research, indicated that in rating of the bridges the interaction between the beams through the slab must be taken into account (Ref. 46).

This phase of the research was sponsored by the Pennsylvania Department of Transportation and the Federal Highway Administration.

2.4 Simulated Inelastic Analysis of the Superstructure

The research program required the development of an analytical modeling scheme which would permit the gradual penetration of material nonlinearity and damage through the depth of the slab and the beams. The methodology employed the discretization of the slab and the beams as an aggregation of multiple layers of concrete, reinforcing bars and prestressing strands, as shown in Fig. 2 (Refs. 47,50). Simulated

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bridge superstructures made of idealized material have been analyzed, and comparisons were made with the other solutions available in the literature. A good agreement was observed. It should be noted that the idealized material followed the laws of perfect plasticity, which is true only for mild steel.

This phase of the research was sponsored by the National Science Foundation.

2.5 Inelastic Analysis of Beams

Mathematical formulation of the beams followed the pattern developed for the idealized case, Section 2.4, that is, the use of layering through the depth of the beam. Nine major activities had to be undertaken: (1) development of necessary relations to express material nonlinearities including the cracking and crushing of concrete and yielding of steel, (2) development of failure criteria for each material, (3) development of mathematical relations for the above and preparation of computer programs, (4) development of the analysis scheme to predict the inelastic response of beams, up to collapse, (5) verification of the predictions through comparison with available test data, (6) extension of the formulation and application to other basic structural components to make further numerical comparisons, (7) assessment of the accuracy of the solution's stability to small errors on the user's part in predicting the geometrical and material properties of the beam, (8) assessment of the amount of flexure versus shear and flexure induced

damage to the beams, and (9) through a simulated model, assessment of the errors that may be introduced by neglecting the torsional stiffness and minor axis bending of the bridge beams acting in unison with the slab.

It was assumed that, as far as the practicing engineer is concerned, the only material property that can be accurately recorded or predicted is the 28 day cylinder strength of concrete and the yield point of steel. Exhaustive trials on the formulation of material proerties have resulted in a universal relationship that can be literally applied to any material (Refs. 23,24,27,28,29,30,32,34,36,37). The formulation also has been applied to beam-column problems because of the vast amount of information available, both analytical and experimental, for further verification. A full agreement was observed (Refs. 14, 26,29,31). The formulation of the analytical development on the prediction of the inelastic response of beams resulted in a computer program named BEAM (Ref. 25). The program has been successfully installed at Pennsylvania Department of Transportation's computational facilities to test the transportability of computer programs from Lehigh University computing center facilities, where the research was conducted, to Penn-DOT facilities, where the programs are required to be operational.

During the conduct of the research it was also decided not to consider the minor axis bending stiffness and torsional stiffness of the bridge beams in the future phases of the research. The studies have indicated that these stiffnesses can be neglected without any loss in accuracy (Refs. 29,33,35,43).

The single most important finding of this phase of the research was that the developed formulation is applicable to steel, so long as no instability occurs, prestressed concrete and reinforced concrete I-, T-, and rectangular beams with minimal input by the user, resulting in a highly accurate (5% error at worst) prediction scheme. It was also observed that the inelastic response of the beams, up to collapse, for all practical dimensions is governed by the flexure.

This phase of the research was sponsored by the National Science Foundation, the Pennsylvania Department of Transportation and the Federal Highway Administration.

2.6 Inelastic Analysis of Reinforced Concrete Slabs

Inelastic analysis of reinforced concrete deck slabs again employed the layering technique mentioned in Section 2.4. The major activities that had to be undertaken were (1) development of stress-strain curves for concrete subjected to biaxial stress field, (2) development of failure criteria for concrete in biaxial stress field, and (3) incorporation of these developments into the overall finite element analysis scheme to predict the inelastic response of reinforced concrete slabs (Ref. 40). Most of the work on the development of biaxial stress-strain and failure had been the first of its kind in the scientific literature. Even some of the more recent work that has appeared in the literature has not included all of the possibilities that the reported research considered.

During the conduct of the research it was observed that (1) the development of membrane stresses in the slab has a substantial effect

on the initiation of the damage; this is a refinement of the classical yield line analysis of the slabs, which considers only the bending of the slabs, (2) as the material nonlinearity and the damage to the slab become more pronounced it is imperative that the stresses induced by the in-plane forces and biaxial bending and their interation be considered; their superimposition would lead to erroneous results (Ref. 41), (3) as compared to the computer simulation of the beams, the simulation of the slabs requires a more refined formulation; otherwise, as the material nonlinearity and the damage start spreading throughout the slab the predicted and the actual response tend to diverge, (4) it is still possible, as in the case of the beams, to define all the stress-strain characteristics and failure criteria for concrete through the use of the 28 day cylinder strength alone, and (5) exclusion of the stresses in the direction perpendicular to the plane of the slab does not alter the results.

This phase of the research was sponsored by the National Science Foundation, Pennsylvania Department of Transportation and Federal Highway Administration.

2.7 Shear Punching Susceptibility of Bridge Decks

During the conduct of the research there was a concern stemming from the experience with the field testing of highway bridges (Ref. 51). It had been stated that since high rises in the slab strains were observed when the wheels are in the vicinity of the strain gages, there is also the possibility that the deck slab will fail due to shear punching, or punching shear failure. Previous studies on the overload

response of reinforced concrete slabs had indicated that unless the load was transferred to the slab over a very limited area, the mode of failure was due to the biaxial flexure of the slab. However, since the formulation was based on the flexural response, if the possibility of the shear punch failure could not be conclusively ruled out, then the overload predictions for the slab, and later of the bridge, would always have be be subjected to manual scrutiny to check the possibility of the development of the shear cone.

The researh has conclusively shown that for the overload vehicles that are encountered in the traffic streams the bridge deck has a factor of safety of about ten against shear punch failure, if the factor of safety against flexural failure is taken as unity (Ref. 20). The field testing of the "Penn State Test Track Bridge," PennDOT Research Project 71-8, under the most adverse loading conditions did not produce shear punching prior to the development of substantial flexural damage (Ref. 19).

Overload vehicles tend to have multiple axles and multiple low pressure tires (Refs. 8,14,38). Since the main cause of the shear punching is the transfer of a heavy load over a very limited contact area, the likelihood of the occurrence of shear punch failure due to overload vehicles is less then remote, to say the least.

This phase of the research was sponsored by the Pennsylvania Department of Transportation and the Federal Highway Administration.

2.8   Inelastic Analysis of Bridge Superstructures

The analysis and simulation techniques and the pertinent computer programs that have been developed for reinforced and pre-stressed concrete beams (Section 2.5), and for reinforced concrete slabs (Section 2.6) were interfaced in accordance with the overall analysis scheme developed for the full bridge superstructure (Section 2.4).   The analytical formulations for the bridge superstructure are highly complex and sophisticated (Ref. 43).   However, since this analysis package essentially consisted of the developments for beams (e.g. Ref. 24) and slabs (Ref. 40), the mastery of the analytical formulations can be greatly simplified if the developments leading to them are understood. The analysis scheme to predict the overload response of the bridge super-structures has resulted in a detailed computer program acronymed BOVA (Bridge OVerload Analysis) (Refs. 42,44).   The computer program and the analysis scheme's accuracy have been verified throughtthe simulation of field test results that have been previously conducted and reported by other researchers (Refs. 4,6,9,10,19).   The investigation was further extended into the determination of the effects of the approximations on the superstructure and loading (Refs. 22,45).   It has been noted that for the five detailed comparisons the results obtained via Program BOVA have a 95% reliability (maximum observed error = 5%).

It has been observed from the computer based simulation of the bridge superstructures and the comparison of the results with field test data that the exclusion of the torsional and minor axis bending stiffness of the beams does not have any adverse effects that can be

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discerned (Refs. 33,35,43).

In the investigation it had been assumed that the primary
mode of failure of the deck slab and the beam, and consequently of the
superstructure, was due to the flexure of the system. Specific compari-
sons with the damage photographs of the field tested bridges and the
computer analysis results have confirmed this assumption. It is also
recognized that for a short span bridge with deep beams the failure of
the beams will be due to the interaction of the shear and flexure. In
Program BOVA provisions have been made to detect such situations and
provide informative messages (Ref. 42).

The research has also indicated that if the vehicle does not
almost fully occupy the width of the bridge, the damage to the super-
structure initiates in the deck slab. If the vehicular loading is almost
equally distributed amongst the beams, then the damage can initiate
either in the slab or in the beams. Prior to the crushing of the beam
or slab concrete substantial cracking in these components will take
place.

Redistribution of the stresses due to the penetration of the
material nonlinearity and the damage to the bridge shifts the load to
an undamaged or less damaged region of the superstructure. If a certain
amount of damage can be permitted then the amount of load that can be
carried is substantially higher than the load level that corresponds to
no-damage limitation.

The maximum deflection criteria for live loading, as prescribed
by AASHTO (Ref. 53), is not a realistic measure for the behavior of the

superstructure. Even when the maximum deflections are well within the limits, the superstructure can still exhibit damage.

If the serviceability limits are to be imposed in the determination of the permissible overload levels, the following are the possible benchmark checks that may be used:

1. Crack depth through the slab

2. Crack depth through the beam

3. Interfacial shear between the beams and the slab

4. Strain or stress levels in the prestressing strands

5. Crack width in the beams

6. Crack width in the slab

7. Margin of safety from reaching the ultimate load of the superstructure

It is the researcher's belief that the above tabulation follows the criticality of the checks in descending order.

Further comments on the serviceability limits and Program BOVA have been included in Chapters 3 and 4 of this report.

A major portion of this phase of the research was sponsored by the Pennsylvania Department of Transportation and the Federal Highway Administration.

2.9 Application of the Research to an Ongoing Field Study

In response to the suggestion of the Pennsylvania Department of Transportation an interactive effort was undertaken with PennDOT Research Project 71-8. While the developments reported in Section 2.8 were nearing their completion, the Test Track Bridge near College Park, Pennsylvania was being tested through the traverse of an overload vehicle of gradually increasing load intensity.

The bridge consisted of two simple spans with 60 ft. span length each. The superstructure had a slight skew and 10.4% super-elevation. It also had six prestressed concrete beams spaced 6 ft.-10 in. apart. After an accelerated testing of the bridge through the repeated passage of the simulated design vehicle, the bridge was subjected to overloading. The overload vehicle consisted of a three axle truck with a total weight of approximately 28½ kips. This truck was used to propel a trailer with two axles, 4 ft. apart. The axle loads of the trailer were varied during the conduct of the test from 40 kips per axle to 120 kips per axle. Each axle had four steel "wheels" covered with flexible material, i.e. no tires!

The bridge superstructure included various types of deck configurations. Some design parameters, even with a given span, were also changed to provide comparisons. Due to the multitude of variables that the experimental researchers had to investigate, it was soon realized that neither as-built-plans of the bridge nor the material properties could be obtained. In order to comply with the very tight

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timetable of the experimental program, educated guesses were made both for the dimensions of the bridge and for the material properties.

The prediction of the overload response of the superstructure and the actual test results showed an agreement. The only discrepancy had been in the penetration of the cracks on the deck slab. The analysis predicted that for a given axle load the cracks would penetrate 1/3 the depth of the slab, and that for about a 20% increase in axle loads the cracks would penetrate 1/2 the depth of the slab. Field investigation through coring of the deck slab showed that the cracks penetrated 58% of the slab for the load level between the two above reported increments. Careful examination of the field test and its results, as well as the computer based prediction of the overload response, has indicated that the actual difference between the predicted and the measured crack depths is much smaller (Ref. 19).

It is interesting to note that both the field test results and the analytical predictions were in full agreement on all critical issues which were later observed in the parametric investigation as well (Ref. 18). The observations of importance are:

1. Damage to the deck concrete in the form of cracking is the first sign of distress due to the overload.

2. In contrast to the belief of some engineers, the negative bending of the deck slab, i.e. over the beam flanges, is not necessarily the first cracking that will occur. In general, as a crude rule of thumb, it can be stated that the cracks at the top of the beam flanges and on the top

surface of the slab will occur at about the same load level

that will cause cracks at the bottom surface of the slab

approximately at midspacing of the beams.

3. Stress levels in the reinforcing bars of the deck slab are

   not high enough, even after major cracking of the deck slab,

   to cause any concern.

4. Damage to the bridge beams in the form of cracking initiates

   after substantial damage to the deck slab.

5. After the initiation of the damage to the deck slab, the

   damage may very well spread both over a large area and

   through the depth after an additional load to the vehicle.

   However, depending upon the vehicular configuration it is

   possible that after the initiation of the damage its spread

   may very well require substantial additional overloads. This

   aspect has been discussed in detail in Reference 18.

This phase of the research was sponsored by the Pennsylvania

Department of Transportation and the Federal Highway Administration.

2.10 Parametric Study

The comparisons between the field testing of six bridges to

"destruction" and prediction of their overload response have been most

satisfactory. However, this has not provided enough insight into the

problem area of "How will commonly encountered bridges in the Common-

wealth of Pennsylvania respond to commonly encountered overload 'vehicle'?"

This question has been answered through the conducted parametric

investigation.

The investigation considered nine bridges, without imperfections, that are designed in accordance with the current Pennsylvania Department of Transportation's design standards. The bridges had span lengths of 40 ft., 70 ft., and 100 ft. They had 5, 7, or 8 beams. For all bridges it was assumed that the beams were spaced at 7 ft.-6 in. The facia beams had an overhang of 3 ft.-9 in.

A total of five overload vehicles were considered, four of which could also be considered as dollies of trailers. The vehicular loading was not defined. The only predetermined parameters were the spacing of the axles, number of wheels for each axle, and out-to-out dimension of the tire print for any given axle. Each vehicle was applied to each bridge, resulting in 45 overload case studies. After initial pilot parametric investigations and also reinterpretation of the previously conducted studies it was decided that the most adverse overload response in the superstructure would be generated when the center of gravity of the "vehicle" was at the midspan of the bridge (Ref. 45). The overload response analysis for each case was conducted from zero live load, i.e. dead weight of the structure only, until the formation of the cracks in any given beam that would penetrate to the prestressing strands. Program BOVA also provided printouts of all stress, deformation and damage information for any load level which caused the initiation and spread of any type of damage to the superstructure.

The results of the 45 case studies have been summarized in Overload Directories. The Directories contain information on the total

vehicular weight levels, maximum compressive and tensile stresses in the slab and beam concrete, maximum interfacial shear between the beam(s) and the slab, and a short summary of the damage to the superstructure. Close inspection of the results has indicated that these Overload Directories can be used in conjunction with the overload permit operations. It is recognized that the Directories can not be used for all permit applications. However, through illustrative examples and guidelines that are developed, based on the researcher's experience with the overloading analysis of various bridges, and included in Reference 18, the applicability of these Directories is not confined to applications that are identical to the case studies analyzed. Through the use of engineering judgment and common sense a large variety of bridges and overload vehicles can still be considered through the usage of the Overload Directories and necessary interpolations. Further comments on the Overload Directories and parametric investigations can be found in Chapters 3 and 4 of this report.

The pilot parametric studies were also conducted for a limited number of cases that were included in the original set of 45 case studies. The pilot study focused attention on the effects of the bridge deck deterioration on the overload response of highway bridges. Two types of deck deterioration were considered: (1) loss of concrete cover at the top of the slab down to the reinforcing bars, and (2) 500 psi reduction in the compressive strength of the slab concrete. The effects of the deck deterioration on the reduction of the load level that will initiate various types of damages have been quantified (Ref. 18).

The major portion of this phase of the research was sponsored by the Pennsylvania Department of Transportation and the Federal Highway Administration.

3. CONCLUSIONS AND RECOMMENDATIONS

The research project on the overloading behavior of beam-
slab type highway bridges was aimed at the development of a computer
based analysis scheme to predict the overload response of right beam-
slab bridges with prestressed concrete I-beams. During the conduct of
the research some observations, that are applicable to all cases inves-
tigated, were noted. The conclusions and observations are as follows:

1. Neither the Commonwealth of Pennsylvania nor the federal
   agencies have any long term programs, activities, actions
   or guidelines based on present technological and scientific
   know-how (1) to determine the effects of overloading on
   highway bridges (2) to assess the adverse effects of over-
   loading and to determine the cost effectiveness of the
   possible damage versus savings that heavier vehicles can
   provide, if any, and (3) to issue, or deny, overload permit
   applications.

2. If some material nonlinearities and damage are permitted,
   recoverable or not, to the superstructure the only existing
   tool to be used in the determination of the extent of the
   damage and the pertinent permit operations is the use of
   computer program BOVA (Refs. 42,43) or the Overload Direc-
   tories reported in Reference 18.

3. The statical indeterminancy of the beam-slab superstructures
   is very high. The accurate and, more importantly, reliable
   prediction of the stress and deformation patterns in the

superstructure requires the use of refined analysis schemes, even for the elastic regime (Refs. 5,15,49,51).

4. The current AASHTO provisions (Ref. 53) with respect to the overloading of highway bridges are ambiguous. The increases in the stresses in the bridge superstructure when subjected to infrequent overload vehicles are not realistic and do not reflect current engineering know-how.

5. Current overload permit operations need to be revised to reflect the advances in engineering (Ref. 57). The preferable direction to take will be a computer based information retrieval system that can be accessed from district offices through the computer terminals.

6. The overload permit "analysis" based on "reverse design processes," e.g. the use of s/5.5 to find the loads carried by the beams, is in most cases inaccurate and usually unconservative.

7. A close interaction between the personnel charged with the inspection and maintenance of the bridges, and the personnel charged with the overload permit applications is highly desirable (Refs. 3,7,57).

8. The overload response of bridges is adversely effected not necessarily by the gross weight of the vehicle, but by the (1) increase in axle loads, (2) decrease in number of tires per axle, (3) decrease in axle spacing, and (4) increase in the number of axles grouped together, as in the case of dollies.

9. For bridges designed under the current design practices the deck slab is more susceptible to damage than the prestressed concrete beams (Refs. 14,18,19,21,43,50).

10. The first indication of overload damage to the superstructure is the cracking of the deck slab concrete (Refs. 14,19,21,43).

11. Bridge decks are not susceptible to shear punch failure. Prior to the attainment of the load level that can cause shear punch failure, the deck will undergo almost total damage due to flexure (Ref. 20).

12. The damage initiation and its spread in the deck slab is due to flexure (Refs. 14,18,19,21,40,43,45).

13. The damage initiation in the beams is due to flexure, starting with the cracking at the bottom of the beam (Refs. 18,19,24,43 45). The provisions in entries No. 15 and 16 should also be noted.

14. Due to their marginal stiffness against torsion and minor axis bending, the primary form of distress in the beams, if any, is due to the primary bending of beams (Refs. 33,35). The provisions in entries No. 15 and 16 should also be noted.

15. Shear stresses in the beams are not critical. However, their presence may amplify the effects of the flexural stresses, causing principle stresses in the beam higher then the flexural stresses (Refs. 43,45).

16. Interfacial shear between the beams and the slab may reach critical values near the supports for short span bridges,

e.g. about 40 ft. or less (Ref. 18).

17. Crushing of slab or beam concrete is very unlikely. Redistribution of stresses will cause more cracking of the concrete rather than the development of the extreme compressive stress zones.

18. Stresses in the reinforcing bars in the slab are very low regardless of the extent of the damage being experienced by the slab (Ref. 19).

19. Reduction of the strength of the deck slab (1) due to the loss of concrete cover down to the top of the reinforcing bars, or (2) due to reduction in the compressive strength of concrete lowers the vehicular load level that can cause damage to the superstructure. The latter is more critical then the former; there is approximately a 20% versus 10% lowering of the load level (Ref. 18).

20. If a certain amount of damage to the superstructure is permitted, then the overload level that can traverse the bridge is substantially higher then the overload level that would have caused no damage. The damage that needs to be considered is the penetration of the cracks in the deck slab down to the top of the reinforcing bars. This substantial increase in the load level, through the acceptance of the damage, is due to the redistribution of the stresses and loads throughout the superstructure. Since most decks already contain cracks, permitting additional cracks of a limited nature will not

greatly endanger the integrity of the superstructure. However, prior to the acceptance of this philosophy a close inspection of "permissible damage" and the implications of the decisions should be clearly defined (Refs. 3,7,18,21).

21. The Overload Directories can be used, at least for a limited number of cases, in overload permit operations (Ref. 18).

22. For uncommon overload cases Program BOVA can be used in overload permit operations (Ref. 42).

23. The accuracy of the prediction of the overload response can be increased through the use of a finer discretization of the bridge superstructure (Fig. 1) and an increased number of layers (Fig. 2). These increases result in an increased computer cost in the execution of Program BOVA.

During the conduct of the reported research some observations were made in regard to the "overloading" and related subjects. The following are the suggestions whose realization may alleviate the problems:

1. It is highly desirable to develop detailed long range plans to solve problems related to overloading. This can be undertaken both at state and federal levels. The planning should not only include the technical areas but policy related issues as well.

2. It is prudent to assume that in the future there will be an increase in overloading of bridges both in terms of the vehicular weights and the frequency of the occurrence of the

overloading (Refs. 8,12,38,46,54,55). Therefore a greater importance should be attached to the issues related to overloading.

3. It is highly desirable to conduct surveys on overload vehicles, both within the Commonwealth and nationwide, to have a reliable and sufficient data base for the number of "overload" vehicles encountered, their axle spacing, axle weights, and number of tires per axle.

4. Initiation of a program that will enable field testing of existing bridges to destruction will reveal very useful information. The use of bridges that are no longer essential can cut down the cost of the test program. It will be highly desirable if these bridges were not built for testing, a situation as such usually leads to a bridge superstructure that will not include possible construction mispractices. Bridges that have deteriorated will reveal even greater information since engineers are more concerned with the strength of bridges that are "borderline cases," rather than those in mint condition. There exists a great gap of information on the actual behavior of skewed bridges.

5. More parametric studies need to be conducted complementing the Overload Directories developed in this research program. Pennsylvania Department of Transportation's Research Project 77-2 is the first positive step in this direction (Ref. 21). The findings of Project 77-2 will not answer all the questions, therefore, additional follow up studies based on the findings

of the project should be seriously considered.

6. It is highly recommendable to have comparisons made between the prestressed I-beam bridge design practices in the Commonwealth of Pennsylvania and other states to determine the applicability of the parametric studies that led to the Overload Directories in this project (Ref. 18) and to PennDOT Research Project 77-2 (Ref. 21).

7. It is imperative that depositories of information and technical experience related to "overloading" be established. Currently, bridge overloading problems have been alleviated through the dedication of bridge engineers at district, state and federal levels. This, unfortunately, is not a solution to the overall problem. Displacement or reassignment of these engineers may very well cause cessation of their dedicated activities to the problem area. However, the identification of an individual(s) or institution to act as a depository will definitely provide a better continuity to the technical activities and information exchange. As can be noted, this is an urgent problem, but it is also a low-profile long-term activity.

8. The initial version of computer program BOVA was developed with prospective users in mind. It was assumed that these users would have at least minimal technical training, but not be experts, and could be instructed in how to make full use of the program after about a day long seminar. As the reported research progressed, the potential and capabilities of the

program were also recognized. Following the suggestions of
the monitors of the research program from the sponsoring
agencies, additions and modifications to the computer program
were undertaken. These activities have definitely made BOVA
a powerful and sophisticated tool. The price that had to be
paid for this change has been greater demand upon the technical
background of the prospective user. In order to revert the
program to a version that will make it simpler to use, at the
expense of giving up some of the potential and sophistication,
changes need to be made. This activity has already started
through the initiation of PennDOT Research Program 77-2,
Implementation of Program BOVA (Ref. 21).

9. It is imperative that the definition of damage, serviceability
   and performance criteria to be used for overload permit appli-
   cations, and for bridge rating, be undertaken at state and
   federal levels (Refs. 18,21,39,42).

10. Studies have already showed that the developed methodology
    and computer program BOVA can be applied to structural con-
    figurations other than bridges (Refs. 16,17,26). Structural
    engineers who are interested in other structural forms should
    be made aware of its potential. This may very well answer
    some of their needs (Ref. 17).

11. It is essential that maximum publicity be given, both at
    state and federal levels, to the general problem area of
    "overloading." This should not necessarily be confined to

bridge engineers only. Most people, bridge engineer or other-

wise, do not have any appreciation, or even a remote awareness,

of the adverse effects of overloading on the transportation

network, including bridges. The current concern is primarily

on the deteriorated state of some of the bridges. It should

be realized that the deterioration may be substantially

accelerated due to the overloading.

4. SUGGESTIONS FOR IMPLEMENTATION

Some of the observations and conclusions that have been pre-
sented in the previous chapter may be considered as having potential for
immediate implementation. However, to have a better assessment of the
general problem area of overloading, and to interpret the suggestions
of the previous chapter with the appropriate relevancy, a brief summary
of the current state-of-the-art will be of assistance.

It has been noted that in the Commonwealth of Pennsylvania,
as well as in other states, overloading of bridges, both due to the
vehicular weight that is beyond the design load levels and to the
deterioration of the bridges, is a common problem. The regulations
governing the movement of the overweight vehicles and loads in Penn-
sylvania require a major re-evaluation and modifications, where needed.
There exist no national realistic provisions for the overloading of the
bridge superstructures. There have been piecemeal attempts by some
states to define the overloading and pertinent permit operations. How-
ever, all known provisions for overloading can be considered as initial,
interim attempts, based on intuition rather than scientifically accepted
assumptions. A study of the overloading, the effects of overloading on
bridges, the allowable damage to the bridges and the definition of over-
load permit operations that can be supported by the current technical
know-how have been initiated by the reported research project. In view
of the complexity of the overall problem area, no major all-inclusive
suggestions can be made herein that will alter problems and operations
associated with overloading.

Towards the long term implementation of the findings of this research project, as well as PennDOT Research Project 77-2, Implementation of Program BOVA, and PennDOT Research Project 77-1, Overloading of Steel Bridges, the following suggestions can be made:

1. Commencement of an investigation of the accuracy and practicality of the current Pennsylvania Code "Regulations Governing the Movement of Oversize and Overweight Loads and Vehicles" (Ref. 57). Until the enactment of more refined provisions, the existing Regulations can be employed as interim provisions. (It should be noted that the author received these Regulations after the completion of all research activities of PennDOT Research Project 71-12. Therefore, an in-depth study of the Regulations has not been possible.)

2. The Overload Directories produced within the framework of the reported investigation can be implemented as they stand. However, PennDOT Research Project 77-2, Implementation of Program BOVA, is developing additional Overload Directories. Therefore, to minimize confusion, the Overload Directories developed in the reported research and those being developed in Project 77-2 should be jointly released.

3. Program BOVA can be implemented as a tool to determine the effects of overloading on prestressed concrete bridges. However, the release of this program as it stands may cause confusion amongst the permit officers and bridge engineers, at district level, due to the fact that Program BOVA is already

under revision to simplify the input and output for usage by the district bridge engineers and permit officers. The simplified version of the program, which will be acronymed BOVAC (Bridge OVerloading Analysis-Concrete) will be simpler to use, at the expense of the loss of some of the capabilities of BOVA. Therefore, it is recommended that Program BOVA not be distributed at the district bridge engineering and permit office level for immediate implementation. For this level of release, it will be preferable to release program BOVAC for general usage.

4. Program BOVA is a powerful tool in predicting the overload response of bridge superstructures, and it has greater capabilities as compared to BOVAC. It is, therefore, recommended that sufficient expertise be developed and maintained at the Bridge Division of the Pennsylvania Department of Transportation for possible usage of the program for unusual, critical and contested cases.

5. Program BOVA can also be made available through the National Technical Information Service to other Departments of Transportation and interested agencies such that they can either implement the program as it stands or they can generate their respective versions through some modifications in the source code of the program.

6. It is suggested that in the issuance of overload permits by any agency the use of reverse design process, i.e. use of

s/5.5 and determination of the beam stresses, be discontinued. This approach is not realistic and does not indicate the substantial stresses that may develop in the deck slab. This should be replaced, until the full acceptance of Program BOVAC, by an analysis scheme that will consider the superstructure as a single entity. "Canned" computer programs employing finite element method for the elastic analysis of the superstructure are already available through many computer manufacturers, consulting firms and software service bureaus.

7. Parallel to the above suggestion, it is recommended that ultimate strength analysis not be employed in the rating of the bridges and the issuance of overload permits. The collapse load for any given prestressed concrete bridge is extremely high, whereas, the load levels that may induce unacceptable damages to the bridge deck slab may be substantially lower than the collapse load.

8. In view of entries 6 and 7 above, it is recommended that permissible overloading of the bridges be related to the serviceability aspects. Limited damage to the bridge deck for occasional overloading should be accepted.

9. According to the research that has been carried out by the author, and the research team, the permissible amount of damage due to the overloading of the bridge superstructure should be limited to the development of the cracks at the top surface of the reinforced concrete bridge deck down to the top of the

reinforcing bars (up to the bottom of the reinforcing bars
for the bottom of the deck).

10. Cracking of the prestressed concrete beams due to overloading
    should not be considered as the limiting value in the definition
    of the permissible overload levels, since prior to the attainment
    of this load level, the bridge deck can undergo substantial
    damage.

11. Deflection of the beams should not be used as a criterion for
    the issuance of the overload permit operations. The damage
    to the bridge deck is due to the noticeably unequal deflection
    of the beams, not due to a large equal deflection of the beams.

12. In the issuance of overload permits, as well as the rating of
    the bridges, great attention should be paid to the extent of
    the deck deterioration in the form of potholes, substantial
    thinning of the wearing surface and the deterioration of the
    concrete due to chemical agents. These factors tend to lower
    the load level at which the damage to the bridge deck begins.

13. To develop the regulations governing the overloading of the
    bridge superstructures and the definitions of the qualitative
    and, especially, quantitative limits, establishment of a "task
    force" at the state level, and, if possible, at the federal
    level is essential. Only a committee as such can provide a
    mechanism with sufficient leverage to transfer the researcher's
    findings and tentative recommendations into fully implementable
    regulations.

5. FIGURES
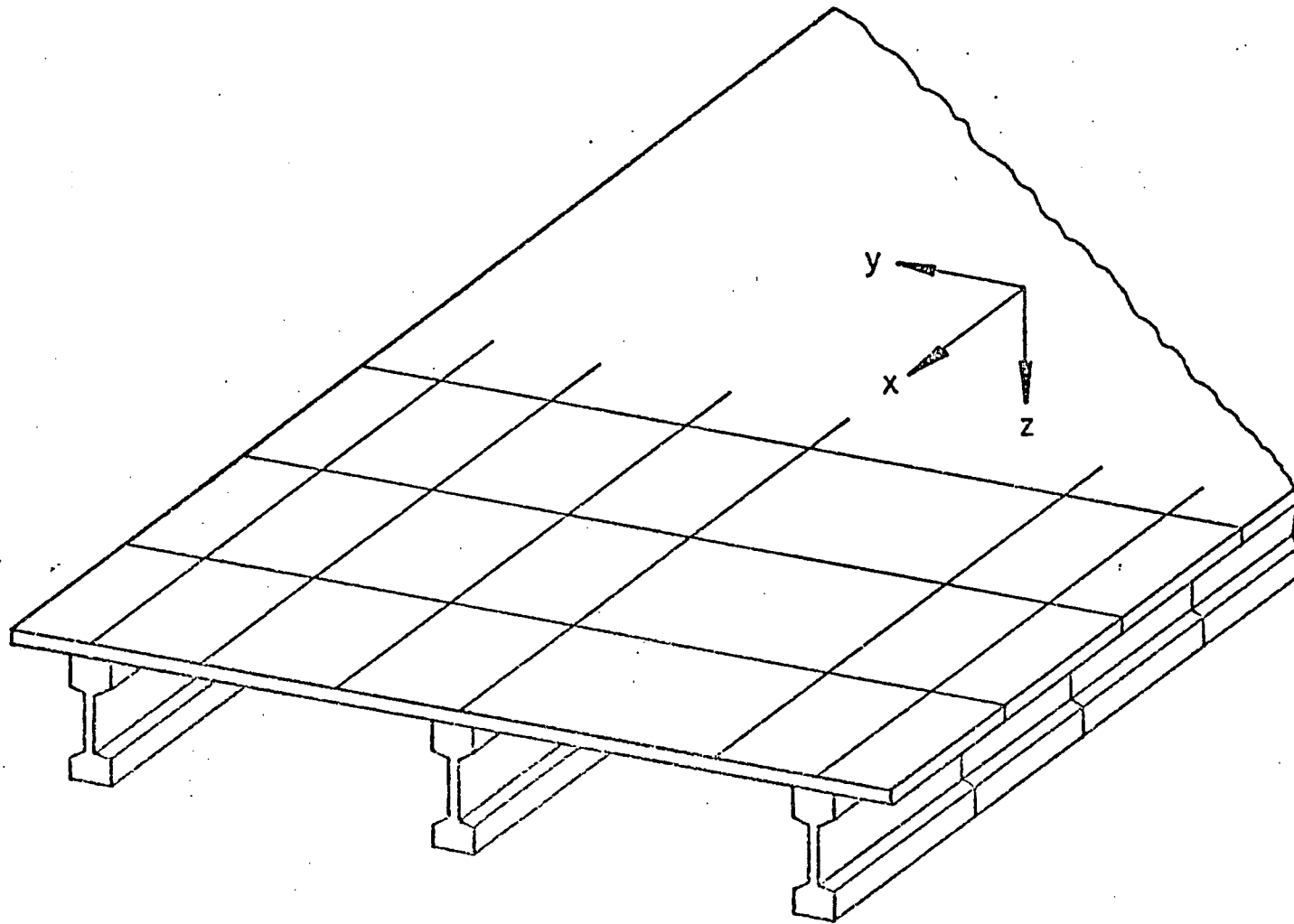
Fig. 1   Finite Element Idealization of
Bridge Superstructure
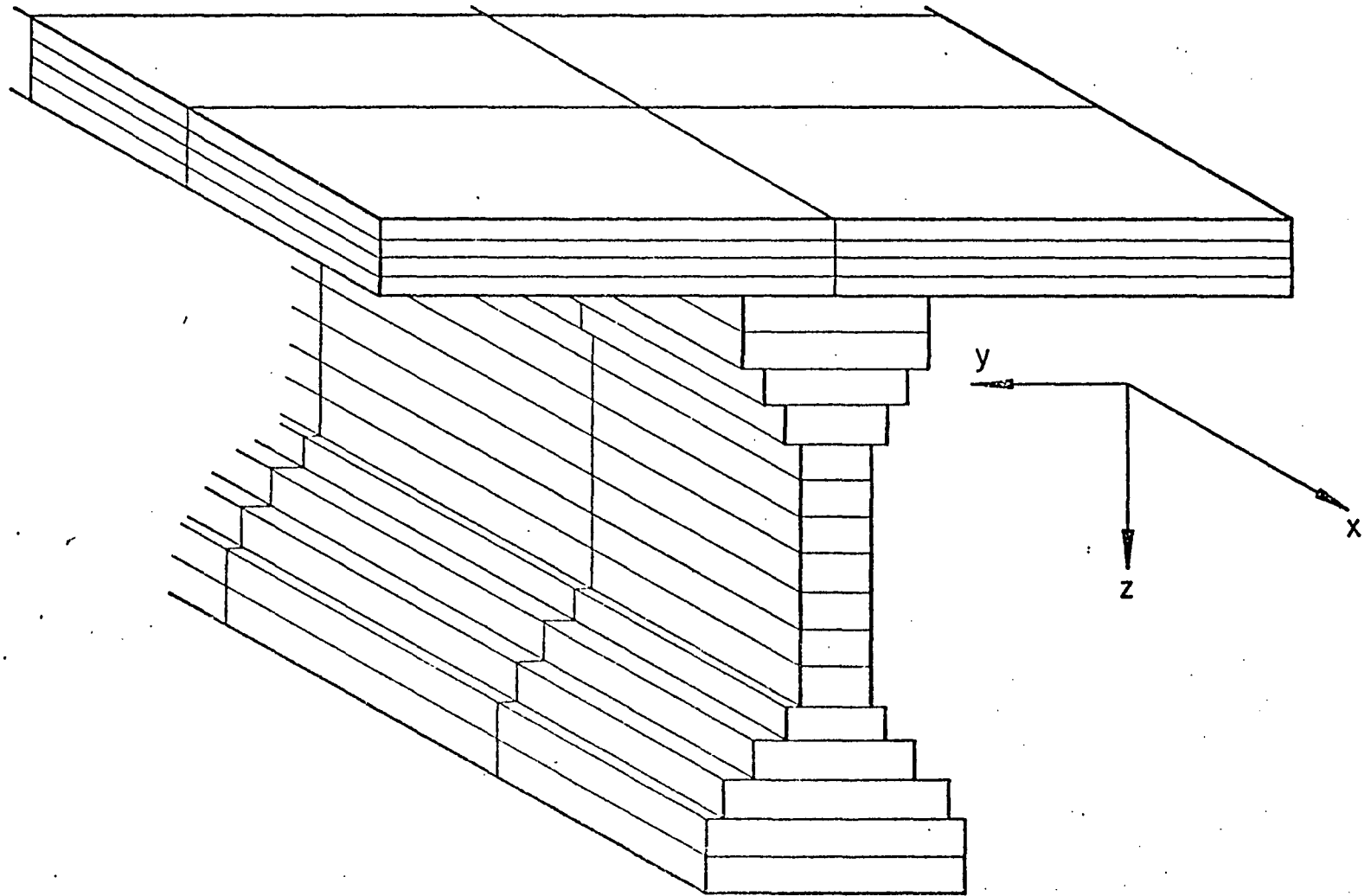
Fig. 2 Layering of Slab and Beam Finite Elements

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