Methods of Strengthening Existing Highway Bridges

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This paper briefly reviews the results of NCHRP Project 12-28(4), Methods of Strengthening Existing Highway Bridges. The initial task in this investigation was a thorough review of international literature to determine strengthening procedures currently being used and to investigate innovative ideas now being considered. The types of structures that show the most need for cost-effective strengthening were identified. A procedure for determining equivalent uniform annual costs was developed to assist the engineer in determining whether to strengthen or replace a given bridge. The culmination of the study was the development of a strengthening manual for practicing engineers. The eight sections of that manual, which contain different strengthening procedures, are briefly summarized in this paper.

About one-half of the approximately 600,000 highway bridges in the United States were built before 1940. Many of these bridges have not been adequately maintained and were designed for lower traffic volumes, smaller vehicles, slower speeds, and smaller live loads than are common today. In addition, deterioration caused by environmental factors is a growing problem. According to FHWA, almost 40 percent of the nation's bridges are classified as deficient and in need of rehabilitation or replacement. Many of these bridges are deficient because their load-carrying capacity is inadequate for today's traffic. Strengthening can often be used as a cost-effective alternative to replacement or posting.

The live-load capacity of various types of bridges can be increased by using different methods such as adding members, providing continuity, providing composite action, modifying load paths, and so forth. Some of these methods have been widely used, but others are new and have not been fully developed. The need to compile, evaluate, and improve existing methods as well as to develop new procedures, equipment, and materials for increasing or restoring the load-carrying capacity of existing bridges was the reason for this investigation. This project is one of a series that was funded by the National Cooperative Highway Research Program (NCHRP) to address the serious bridge problems confronting the United States. The purpose of this paper is to summarize the results of NCHRP Project 12-28(4), Methods of Strengthening Existing Highway Bridges.

The objectives of this investigation were to evaluate the feasibility and cost-effectiveness of current strengthening methods as applied to various types of bridges and to identify cost-effective innovative methods. The objectives required completion of the following tasks:

Task 1: Thoroughly review available literature and contact appropriate organizations to identify, describe, and categorize methods for strengthening existing highway bridges. Innovative ideas as well as established methods should be considered.

Task 2: Determine which types of structures show the greatest need for broad application of cost-effective techniques for strengthening.

Task 3: Evaluate the cost-effectiveness of each method for strengthening bridge structures. Identify new materials and innovative techniques for further study.

Task 4: Prepare a manual for use by practicing engineers that describes the most effective techniques for strengthening existing highway bridges.

Task 5: Prepare a final report documenting all research. The manual prepared in Task 4 should be the main entity of the final report. The additional findings of the investigation should simply provide supplementary or background information.

The final report of this investigation [NCHRP 12-28(4)] was submitted to NCHRP in July 1987; this report has recently been published by the Transportation Research Board as NCHRP Report 293 (*1*). In the following sections the approach taken to complete Tasks 1 through 4 and a brief summary of the results will be presented.

TASK 1

As noted earlier, the purpose of Task 1 was to determine what techniques and procedures are now being used to strengthen existing bridges.

The research team used three different approaches to obtain the desired information: literature review, questionnaires, and personal correspondence.

Highway Research Information Service and the Computerized Engineering Index were searched to obtain articles in English on bridge strengthening. In an attempt to locate German and French articles, volume indexes from 1945 to the present were reviewed. Over 500 articles on bridge strengthening and closely related areas were located. Of these articles, approximately 95 were written in a foreign language. Over 375 of the articles located were included in the bibliography of the final report (*1*). In recent years FHWA and NCHRP have sponsored several studies on bridge repair, rehabilitation, and

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retrofitting. Because these procedures also increase the strength of a given bridge, the final reports of these investigations (*2–12*) are excellent references. Note that the references have been listed in chronological order. Two of these references (*3, 4*) are of specific interest in strengthening work. Reference 3 is an FHWA investigation into methods of increasing the load-carrying capacity of bridges whose capacities are inadequate for current service loads, and Reference 4 presents several techniques for increasing the capacity of various bridge components. Two questionnaires were developed to obtain unpublished information on bridge-strengthening techniques and to identify agencies involved with bridge strengthening. Questionnaire 1 was developed for distribution to government bridge engineers, consultants, and members of various technical committees, and Questionnaire 2 was developed to obtain information from manufacturers of products related to bridge strengthening. A total of 767 questionnaires was mailed; the response rate was slightly over 38 percent. The state bridge engineers had the highest response rate of all the groups surveyed; all but 3 of the 50 state bridge engineers returned the questionnaire. This high rate of response can be partially attributed to their interest and experience with bridge strengthening.

The majority of the respondents had successfully employed one or more techniques to strengthen a given bridge. The following list of strengthening techniques was provided on the questionnaires for reference to assist the respondents:

1. Replace an existing deck with a lighterweight deck.
2. Provide composite action between deck and supporting members.
3. Increase the transverse stiffness of bridge deck.
4. Replace deficient members.
5. Replace structurally significant portions of deficient members.
6. Increase the cross section of deficient members.
7. Add supplemental members.
8. Poststress members.
9. Add supplemental spanning mechanisms.
10. Strengthen critical connections.
11. Add supplemental supports to reduce span lengths.
12. Convert a series of simple spans to a continuous span.
13. Other.

Shown in Figure 1 are the responses to one of the questions on the survey that requested information on strengthening procedures that had been used; the strengthening method reference numbers correspond to those on the foregoing list. The survey results indicate that replacing deficient members and increasing the cross section of deficient members have been the two most frequently used strengthening techniques.

To locate foreign published and unpublished bridge-strengthening information, the research team made personal contacts with colleagues in foreign countries as well as in the United States. Over 70 different individuals and agencies were contacted for such information. Included in this list are the 21 foreign members of the Organisation for Economic Cooperation and Development (OECD) Committee. This group met in Paris in 1983 and developed a report entitled *Bridge Rehabilitation and Strengthening* (*13*). The report reviewed

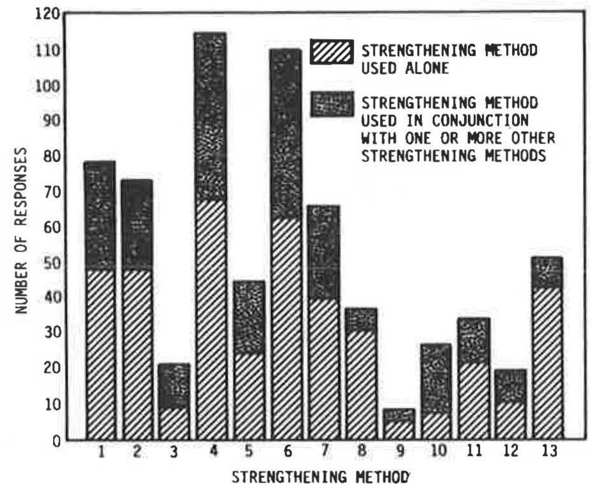

FIGURE 1 Number of responses for strengthening methods 1–13 (see section on Task 1 for description of strengthening methods).

the needs, policies, and techniques used for bridge rehabilitation and strengthening in the OECD member countries. The material provided by a large number of the respondents was quite valuable and has been included in various sections of the final report.

TASK 2

Task 2 involved determining the types of structures that show the most need for cost-effective strengthening. The research team used data from the previously described questionnaires, data in the National Bridge Inventory (NBI), and a limited number of site inspections to address this task. Preliminary findings from this task have been published elsewhere; thus only limited information on this task will be presented in this paper. The most direct approach to determine the types of bridges in need of strengthening is to examine the improvements recommended by bridge inspectors in the NBI. For the 15 common bridge types, inspectors recommended some type of improvement in more than 40 percent of the bridges. As can be seen in Figure 2, the overwhelming choice of improvement, accounting for two-thirds of the recommendations, was replacement due to condition. The inspectors' recommendations, if followed and extrapolated to all bridges, would require that one-third of the nation's bridges be replaced in the near future. Also shown in Figure 2 is that only approximately 1 percent of the recommendations were to strengthen bridges. There are several probable reasons for the few recommendations for strengthening; for example, inspectors did not recognize strengthening as a means of prolonging bridge life, inspectors in some states did not have strengthening as an option, and limitations in the NBI coding system.

For those bridges for which strengthening was recommended, the responses ranked by number and bridge type are shown in Figure 3. The recommendations for strengthening steel stringer bridges account for more than one-half of the recommendations. The next four bridge types in the ranking are steel-through-truss, steel-girder floor-beam, timber stringer, and concrete slab. Although there is some variation in

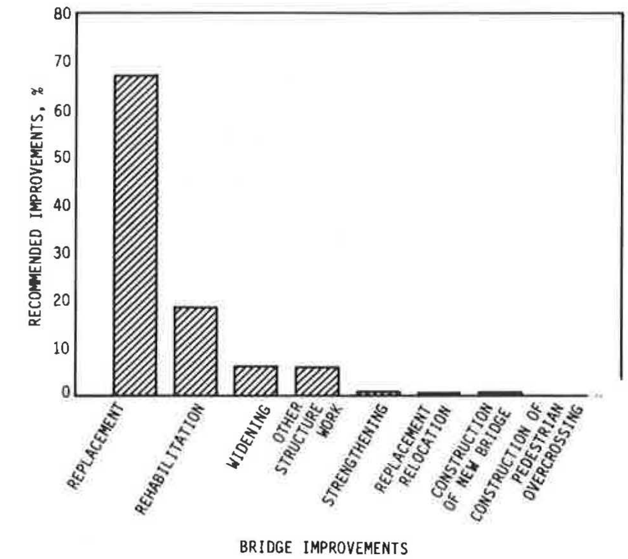

FIGURE 2 Bridge improvements recommended by inspector (NBI).

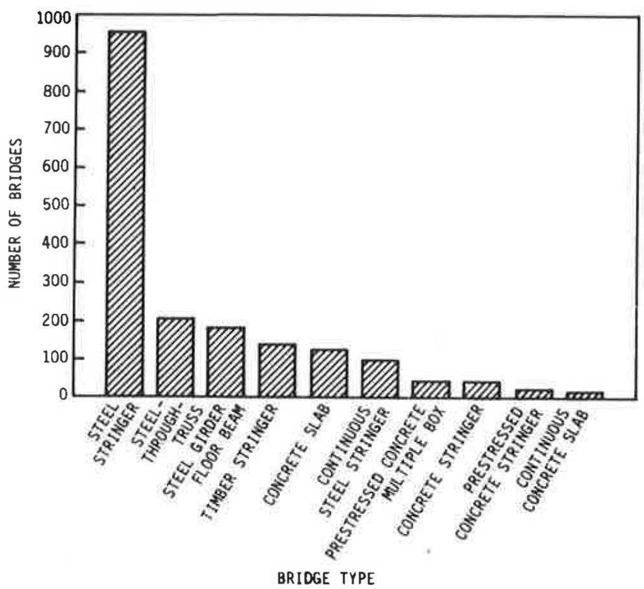

FIGURE 3 Strengthening recommended by inspector, ranked by bridge type (NBI).

which bridges show the greatest need for strengthening, data from the questionnaires and site visits essentially agree with the NBI data. To develop some concept of the urgency of the strengthening needs, the number of anticipated bridge retirements was examined for each of the common bridge types. A representative sample of the type of curve showing anticipated bridge retirements is given in Figure 4 for steel-stringer bridges. The dashed line represents the number of bridges constructed in each 5-year period. Steel-stringer bridges constructed in 1900 and all previous years are represented by the first point on the dashed line. The average life, 57 years in this case, was computed from NBI data for each bridge type by adding the age computed from the year built and the estimated remaining life. The solid line in Figure 4, which represents anticipated bridge retirements, was obtained by extending the

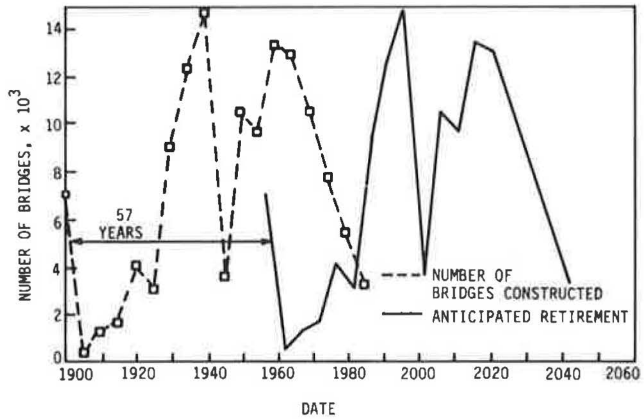

FIGURE 4 Number of steel-stringer bridges constructed and anticipated retirements by 5-year periods (NBI).

construction date into the future by the average life. Although the average life may contain some inaccuracies, it is the best statistic available in the NBI for predicting bridge life.

Figure 4 [and the figures for other types of bridges presented in the final report (*1*)] indicate which types of bridges have large numbers of anticipated retirements in the near future; these bridges show a definite need for effective strengthening methods.

TASK 3

Task 3 consisted of two separate parts: the development of a procedure for determining the cost-effectiveness of strengthening methods for various bridges and the identification of new materials and innovative strengthening techniques.

The bridge engineer has three alternatives when faced with a bridge having a deficient load rating: (a) replace the existing bridge, (b) strengthen the existing bridge (which includes selecting the "best" strengthening method from those available), or (c) leave the existing bridge in its present state. To assist the engineer in making this decision, an equivalent uniform annual cost (EUAC) procedure was developed that makes possible cost comparisons between alternatives of different economic lives. A related paper, Cost-Effectiveness Analysis for Strengthening Existing Bridges (*14*), provides additional background and detail on the economic model.

Listed below are various factors that are considered in the economic analysis models:

Replacement structure first cost: The initial replacement cost has the greatest effect on the EUAC for the replacement model.

Structure service life: Information obtained indicated that a minimum service life of 50 years is commonly assigned to new structures in a life-cycle cost analysis.

Interest rate: Although difficult to predict over a long time period, interest rate significantly affects the EUAC. In general, a higher interest rate favors future expenditures (i.e., strengthening), whereas a lower interest rate favors the immediate expenditure of capital (i.e., replacement).

Bridge maintenance costs: This factor is probably the most difficult life-cycle cost to predict. However, improvements in

bridge maintenance accounting procedures should soon provide data to make more accurate forecasts possible.

Level-of-service factor: This factor is a measure of the cost difference in the level of service provided to the road user between a new and an existing bridge. Level-of-service factors as presented in this model are principally functions of bridge geometry.

Maintenance of essential traffic flow: This construction aspect is very situation dependent and is difficult to quantify accurately.

In the search for new material that might have application in bridge strengthening, essentially no new materials were identified that would be suitable for use in bridge strengthening. Composite materials—that is, materials consisting of two or more distinct parts—were the only "new materials" identified. Composite materials are new to the construction industry; however, they have been used in the aircraft industry for over 20 years. Although composite materials are sensitive to the environment, their main disadvantage in bridge work is the cost. The procedure of bonding steel plates to steel and to concrete is somewhat related to the topic of new materials. Some work on bonding steel to steel has been done in the United States; however, no work has been done in the area of bonding steel plates to concrete. Other countries, such as the United Kingdom and Japan, have been bonding steel plates to concrete for strengthening for over 20 years. Although a literature review of bonding steel plates to concrete has been included in an appendix to the final report, this procedure has not been included in the strengthening manual.

TASK 4

For the information accumulated in Task 1 to be useful to the practicing engineer, it must be organized and presented in a manual format that is readily accessible and easy to use. The development of such a manual was the objective of Task 4. The strengthening manual obviously could be organized by bridge type or by strengthening method. After a conference with the project panel, it was decided to organize the strengthening manual by strengthening method. Although the procedures have been placed in sections according to the method or procedure, for the convenience of the user, a table is provided that is arranged according to bridge type. In the table, the user is referred to a section or sections in which strengthening information for a particular bridge may be found. Obviously, a single strengthening procedure is applicable to more than one type of bridge or stringer.

Strengthening procedures included in the manual are procedures that have been successfully used in the field or have been sufficiently tested in the laboratory so that they can be employed in the field with minimal difficulty. Each strengthening procedure in the manual includes a description of its use, a description of its limitations, and basic cost information. For most procedures, decision aids are provided to assist users in determining the adequacy of the strengthening procedure for particular situations. For several of the procedures, design aids are also given to assist the users. References are provided for each strengthening procedure, describing where the technique has been employed and where additional information may be obtained.

Every effort has been made to present the different strengthening techniques in clear, practical formats to facilitate their use. However, because of the wide range of variables involved (e.g., span lengths, amount of overstress, and type of loading), most of the strengthening systems presented are conceptual, and the designs and dimensions, where given, are for illustration only.

Described in the following paragraphs are the eight sections of Chapter 3 of the final report in which the various strengthening techniques and procedures are categorized. A brief description of the material in each section is presented.

Lightweight Deck Replacement

One of the more fundamental approaches to increase the live-load capacity of a bridge is to reduce the dead load. Significant reductions in dead load can be obtained by removing an existing concrete deck and replacing it with a lighterweight deck. Lightweight deck replacement is a feasible strengthening technique for bridges with structurally inadequate but sound steel stringers. Several types of lightweight decks, including steel grid, Exodermic, laminated timber, lightweight concrete, and aluminum and steel orthotropic plate, are available. Decision aids are included to indicate the relative increase in live-load capacity for each type of lightweight deck.

Providing Composite Action Between Bridge Deck and Stringer

Modification of an existing stringer and deck system to a composite system is a common method of increasing the flexural strength of a bridge. The composite action of the stringer and deck reduces not only the live-load stresses but also deflections as a result of the increase in the moment of inertia. Composite action can effectively be developed between steel stringers and various deck materials, such as normal-weight reinforced concrete (precast or cast-in-place), lightweight reinforced concrete (precast or cast-in-place), laminated timber, and concrete-filled steel grids. In general, composite action is slightly more beneficial in short spans than in long spans, and the larger the stringer spacing, the larger the stress reduction when composite action is added.

Increasing Transverse Stiffness of a Bridge

Increasing transverse stiffness is applicable only as a secondary method for strengthening a bridge. Transverse stiffening can increase the rating of a bridge but does not increase the overall longitudinal moment strength. Increasing the transverse stiffness of a steel-stringer bridge can reduce live-load stresses in stringers by as much as 15 percent. Maximum reductions occur for interior stringers in wider and longer span bridges.

Improving the Strength of Various Bridge Members

One of the most common procedures used to strengthen existing steel stringer bridges is the addition of steel cover plates to

existing members. The additional steel is normally attached to the flanges of existing sections, thus increasing the section modulus and thereby increasing the flexural capacity of the member.

A common method of strengthening compression members in steel-truss bridges is to add steel cover plates to the existing members. The steel cover plates will increase the cross-sectional area of the members and, if properly applied, will also reduce the slenderness ratio of the compression member.

The shear strength of reinforced concrete beams or prestressed concrete beams can be improved by adding external steel straps, plates, or stirrups. For more efficient use of the material added, the new material should be posttensioned so that it carries both dead and live loads.

Improving the strength of timber or concrete piles and pier columns can be achieved by encasing the column in a concrete or steel jacket. Jacketing, which may be applied to the full length of the column or only to severely deteriorated sections, increases the cross-sectional area of the column and reduces the column's slenderness ratio.

Adding or Replacing Members

Reinforced concrete, prestressed concrete, steel, and timber stringer bridges can be strengthened by the addition or replacement of one or more stringers. Adding stringers not only increases the deck capacity, but also reduces the magnitude of the loads distributed to the existing stringers.

Adding supplementary members to truss frames is most commonly applied to Warren and Pratt trusses. The supplementary members are normally most effective in reducing the unbraced length of the top chord member, which can increase the load capacity of the top chord by as much as 15 to 20 percent.

Posttensioning Various Bridge Components

Since the 19th century, timber structures have been strengthened by means of king post and queen post tendon arrangements. These arrangements are still in use today; however, since the 1950s, posttensioning has been applied as a strengthening method in many more configurations to almost all common bridge types. A review of the engineering literature revealed that approximately one-half of the reported uses of posttensioning for bridge strengthening are for the current decade. Posttensioning can be applied to an existing bridge to meet a variety of objectives: relieve tension overstresses with respect to service load and fatigue-allowable stresses, reduce or reverse undesirable displacements, add ultimate strength to an existing bridge, and change basic behavior of a bridge from a series of simple spans to continuous spans.

Strengthening Critical Connections

The types of connections addressed in the manual include cover and splice-plate connections as well as truss connections. Although several methods of strengthening the various types of connections are presented in this section, only two will be briefly described here. One of the more common joint-strengthening techniques is to replace loose or broken rivets with new high-strength bolts. These bolts increase the shear capacity and have been shown to increase the fatigue life of the connected material by reducing fatigue cracking. The use of high-strength bolts at the ends of welded cover plates has also been shown to significantly reduce or eliminate the fatigue cracking often associated with the ends of cover plates.

Developing Additional Bridge Continuity

There are two basic methods of adding continuity to a given bridge. Supplemental supports can be added to reduce the span length and thereby reduce the maximum positive moment in a given bridge. By changing a single-span bridge to a continuous, multiple-span bridge, stresses in the bridge can be altered dramatically, thereby improving the bridge's maximum live-load capacity. Even though this method may be expensive, it may be desirable in certain situations. Several adjacent simple spans may be converted into a continuous span by connecting the simple spans together with moment and shear-type connections. The desired decrease, however, is accompanied by the development of negative moment over the interior supports.

SUMMARY

The results of a study on the various methods of strengthening highway bridges have been presented. The literature review resulted in a bibliography of more than 375 references. Types of structures that show the greatest need for cost-effective strengthening techniques were identified; these are steel stringer bridges, timber stringer bridges, steel-through-truss bridges, and steel-girder floor-beam bridges. An economic analysis for determining the cost-effectiveness of the various strengthening procedures, developed as part of the investigation, is briefly described. The major effort of the study was the development of a strengthening manual for use by practicing engineers. The organization of the strengthening manual and a brief description of the information included have been presented. In the opinion of the authors, the final report of the project in question (*1*) is an excellent reference for engineers faced with the problem of strengthening a deficient bridge.

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