NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 86

# EFFECTS OF TRAFFIC-INDUCED VIBRATIONS ON BRIDGE-DECK REPAIRS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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# EFFECTS OF TRAFFIC-INDUCED VIBRATIONS ON BRIDGE-DECK REPAIRS

**DAVID G. MANNING**
**Georgetown, Ontario, Canada**

*Topic Panel*

CHARLES J. ARNOLD, *Michigan Department of Transportation*
JOHN E. BUKOVATZ, *Kansas Department of Transportation*
H. D. BUTLER, *Texas State Dept. of Highways and Public Transportation*
WILLIAM P. CHAMBERLIN, *New York State Department of Transportation*
ALFRED D. DONOFRIO, JR., *Delaware Department of Transportation*
DONALD J. FLEMMING, *Minnesota Department of Transportation*
GEORGE HARPER, *Federal Highway Administration*
PETER A. KOPAC, *Federal Highway Administration*
KENNETH R. WHITE, *New Mexico State University*

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TRANSPORTATION RESEARCH BOARD
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## NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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## PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

## FOREWORD

*By Staff*
*Transportation Research Board*

This synthesis will be of special interest to engineers concerned with placement of concrete for construction or repair of bridge decks. Recommendations are provided for restoring, patching, and widening bridge decks in the presence of traffic.

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Administrators, engineers, and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information often is fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem frequently is not assembled in seeking a solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of synthesizing and reporting on common highway problems. Syntheses from this endeavor constitute an NCHRP report series that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems.

Engineers need to know whether a bridge must be closed while deck repairs are being carried out or to what extent traffic should be controlled during placement and curing of the concrete. This report of the Transportation Research Board concludes that traffic can be maintained on the bridge while concrete is placed in deck repairs, overlays, widenings, or replacements.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

## CONTENTS

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# EFFECTS OF TRAFFIC-INDUCED VIBRATIONS ON BRIDGE-DECK REPAIRS


## SUMMARY

As the number of bridges requiring rehabilitation increases, engineers are faced more frequently with the decision on whether to close a bridge to traffic while repairs are carried out. The possibility of damage to fresh concrete has made decision making on appropriate traffic-control measures difficult. If traffic-induced vibrations are detrimental to fresh concrete, failure to implement controls could have an adverse effect on deck performance. If the vibrations have no significant consequences but traffic is detoured off the deck, additional costs may be incurred by both the agency and the road user.

Most agencies maintain traffic on a deck during construction of a concrete overlay or widening, although several impose speed and weight restrictions on vehicles. On divided highways, lane closures have a better safety record and are considerably less expensive than the construction of temporary median crossovers.

Vehicles cause bridges to vibrate when the vehicle receives an initial disturbance, such as passage over an expansion joint or roughness in the approach pavement or deck surface. The frequency and amplitude of the vibration are the result of the interaction between the vehicle's suspension system and the dynamic response of the bridge. The largest amplitudes of vibration occurs when the natural frequencies of the vehicle and the bridge are the same; this usually occurs within the range 2 to 5 Hz. Maintaining a smooth approach pavement and a smooth transition at expansion joints and ramps is a more effective way of reducing the amplitude of traffic-induced vibrations than speed and weight restrictions. Speed restrictions should be established using the safety of the road user and work crews as the main criterion.

Internal vibrators used to consolidate concrete operate at frequencies within the range of 50 to 200 Hz and develop peak particle velocities in the concrete of more than an order of magnitude greater than those resulting from traffic-induced vibrations. Well-proportioned concrete is very tolerant of low-amplitude, low-frequency vibrations during the period of setting and early strength development.

Concrete overlays have been widely used as a second stage in the construction of new decks, as preventive maintenance on decks built without a protective system, and in the rehabilitation of deteriorated decks. Although overlays appear vulnerable to cracking, debonding, and differential consolidation under the action of traffic-induced vibrations on the fresh concrete, none of the surveys conducted has identified defects that could be attributed to traffic on the deck at the time of construction. The only factor that has been found to have a significant effect on the number of defects in concrete overlays is the length of time during which the overlay has been in service.

Concern for the performance of concrete in full-depth repairs, widenings, and deck replacements has focused on the effect that traffic-induced vibrations may have on longitudinal cracking and lack of bond with the reinforcement in the fresh concrete. Investigations of widenings in California, Georgia, Michigan, and Texas have revealed only minor problems in performance; these were not attributable to vibrations from traffic. The maximum curvature in the fresh concrete in a typical bridge widening is less than the curvature necessary to cause cracking. Field and laboratory measurements have shown that traffic-induced vibrations do not cause relative movement between fresh concrete and embedded reinforcing steel. Any benefits from temporary shoring have not been proved.

The report concludes that there is insufficient evidence to show that traffic-induced vibrations have an adverse effect on *good-quality* concrete placed in bridge-deck repairs, overlays, widenings, or replacements. There is no justification for changing the present practice of many agencies of maintaining traffic on the deck during construction. The need for further research has not been identified.

CHAPTER ONE

# INTRODUCTION

## BACKGROUND

Many bridges have been repaired or widened while traffic has been maintained on the structure. However, the general opinion has been expressed that concrete in overlays and widenings is more durable when placed in the absence of traffic. Many design and construction engineers have voiced concern that defects in freshly placed concrete have been caused by traffic-induced vibrations. Differential consolidation of the concrete, lack of bond between the reinforcing steel and the concrete, and bond failure between new and existing concrete have been cited as defects that may result from vibration of the concrete caused by traffic during the period of setting and early strength development.

The possibility of damage to the concrete has made decision making on appropriate traffic-control measures difficult. Where a detour already exists, it makes sense to eliminate the risk of traffic-induced vibrations that may have an adverse effect on the performance of the restored deck. Similarly, where traffic, particularly trucks, can be prohibited from lanes adjacent to concrete placing operations without a major disruption in the flow of traffic, the risk of damage can readily be minimized. However, such situations have been the exception. In most locations, detours reduce safety levels and are expensive and often politically undesirable; lane closures seriously restrict the flow of traffic.

Design engineers require more information than has been available to determine to what extent traffic should be controlled. If traffic-induced vibrations are detrimental to fresh concrete, failure to implement controls could have an adverse effect on deck performance. If the vibrations are not of consequence, and traffic controls are imposed beyond those required for the safety of construction personnel and the road user, there is an unnecessary, negative economic impact on the road user. This uncertainty has led several states to adopt compromise measures, such as speed and weight restrictions during the period of concrete placement and early strength gain. Criteria for selecting speed and weight limits have not been established and decisions are being made on the basis of engineering judgment.

## PURPOSE OF SYNTHESIS

This synthesis was undertaken to determine the effects of traffic-induced vibrations on freshly placed concrete in bridge-deck repairs and widening. Secondary objectives (if defects in performance resulting from traffic-induced vibrations were identified during the study) were to (a) recommend construction procedures and traffic-control criteria to minimize the effects of vibrations and (b) identify areas in which further research is needed.

A comprehensive literature study of the effects of traffic-induced vibrations on concrete, and on the bond to reinforcement and previously placed concrete, during the period of setting and early strength development, was conducted. The nature of traffic-induced vibrations is summarized and their effect on fresh concrete is compared to the effect of vibrations from other sources such as blasting and construction activities. An extensive list of references is included and relevant research in progress is identified.

Particular emphasis has been placed on reports of the field performance of concrete repairs and widenings. However, because of the limited data and the lack of reports directed at determining the effects of traffic-induced vibrations, the following two procedures were used to gather information:

1. A nationwide survey of current practices was conducted to determine the traffic control procedures in use at the present time and the basis for existing policies. Deficiencies thought to be the result of traffic-induced vibrations were identified and all positive responses were followed up. A summary of the responses is contained in Appendix A.
2. A brief study was conducted in which the performance of bridge deck overlays in three jurisdictions was observed. The site visits included both overlays that were placed while traffic was maintained on the deck and some that were not. The results of this study are reported in Appendix B.

## TRAFFIC CONTROL DURING BRIDGE REHABILITATION

### General Requirements

Part VI of the *Manual on Uniform Traffic Control Devices for Streets and Highways* (*1*) details the minimum desirable traffic control standards for construction and maintenance operations on streets and highways. The manual sets forth principles and standards that are applicable to both rural and urban areas and directed to ensuring the safe and expeditious movement of traffic through construction and maintenance zones and the safety of the work force. However, where special complexities or hazards exist, precautions in addition to those given in the manual are necessary (several agencies have prepared standard work site layouts to satisfy their own needs).

The protection required at a site is a function of the location of the site, the speed and volume of traffic, the nature and duration of the work, and the potential exposure to hazards. The formulation of a traffic-control plan early in the planning stage of a contract for bridge rehabilitation or widening is most important. This traffic-control plan should include such items as signing, application and removal of pavement markings, scheduling, procedures for channelization and detours, placement and maintenance of traffic-control devices, traffic regulations, publicity, inspection, and enforcement. Limited-access highways, especially those in urban areas, require special attention (*2–5*) because of the large volumes of high-speed traffic.

### Requirements for Divided Highways

Three basic alternatives exist for handling traffic during maintenance or construction projects on divided highways (*3*):

1. Roadway closure and off-site detours,
2. Detours within the right of way, or
3. Lane closures and constrictions.

Off-site detours are used infrequently during bridge rehabilitation projects because there is usually considerable opposition from local residents, especially in urban areas, to diverting freeway traffic onto local roads and streets. Also, situations in which the traffic cannot be accommodated within the right of way occur infrequently.

For detours within the right of way, temporary median crossovers have been used by many states during the repair of parallel bridges. The usual procedure is to close one roadway and maintain two-way traffic on the other roadway, permitting work to be completed on each bridge in the absence of traffic. Experience with lane reversals has not been very satisfactory: the frequency of head-on collisions, especially on long stretches of two-way operations on which no separation devices were provided, caused the Federal Highway Administration to issue an amendment to the federal regulations in 1979 (*6*) to permit two-way operation on one roadway of a normally divided highway on federal-aid projects only when other methods of traffic control are determined not to be feasible. Where two-way traffic must be maintained on one roadway, separation of the traffic lanes must be provided and concrete barriers having a safety profile, or an approved alternative, must be used at transition zones. A subsequent proposal has been prepared (*7*) to modify the 1979 amendment to allow greater flexibility in the provision of separation devices while strengthening the requirement to provide positive barriers where dictated by individual project conditions.

The combination of poor safety records, costs of providing separation devices and temporary median crossovers, and uncertainty over the need to remove traffic from bridges undergoing repair or widening has caused a number of states to use only lane closures or constrictions during the repair of freeway bridges. Responses to the survey conducted as part of this study (see Appendix A) indicated that all states (except Hawaii) permit traffic on a bridge undergoing partial depth repairs, and, of the 45 respondents, only Hawaii and South Dakota routinely close bridges undergoing widening or full-depth repairs.

The savings that may be realized from the use of lane closures instead of temporary median crossovers are substantial. Because traffic control costs are typically in the range of 10 to 20 percent of the total cost of a rehabilitation contract, the potential for savings is clear. Actual savings must be calculated for specific site conditions. On a particular project in Minnesota, the savings resulting from the elimination of temporary median crossovers were estimated to be more than $104,000. The project involved the application of concrete overlays to two sets of three-span, parallel bridges on a divided highway. The contract can be considered typical for the repair of bridges over minor crossings on Interstate and divided highways.

Traffic-control plans for projects involving lane closures or constriction should consider the requirements for safety and minimal disruption to the flow of traffic and the need for safe, efficient, and economical work procedures. In some cases, shoulder detours may be used in conjunction with reduced lane widths to retain the original number of traffic lanes. In other cases, the work cannot be executed without reducing the number of lanes. Temporary concrete barriers are commonly used for lane closures. In addition to physically separating traffic from the work crews, they are effective in minimizing the distraction of motorists by the construction activities (*5, 8*). Traffic-control measures on freeways are discussed in detail in *NCHRP Synthesis of Highway Practice 1 (2)*, which also includes guidance on public-information campaigns, coordination of traffic-control activities with other agencies, training of personnel, and preparation and implementation of operational plans.

CHAPTER TWO

# TRAFFIC-INDUCED VIBRATIONS

### GENERATION AND TRANSMISSION OF TRAFFIC-INDUCED VIBRATIONS

Traffic-induced vibrations are generated mainly by fluctuations of wheel contact forces as vehicles travel over irregularities in the road surface (*9*). Variations in contact forces between the wheels of a vehicle and the road surface resulting from the transfer of out-of-balance forces generated within the vehicle (e.g., from the drive train or unevenly balanced tires) are not significant. Vibrations generated by direct transmission of pressure waves through the air arising from the size, shape, and speed of the vehicle (the bow wave effect) and by pressure fluctuations from the engines, exhaust, or other noises generated by the vehicle can produce movements in large flexible components in buildings, but are not of practical significance in the dynamic response of bridges.

Vehicles cause bridges to vibrate when the vehicle receives an initial disturbance such as passage over an expansion joint or an irregularity in the approach pavement or deck surface. The nature of the vibration is determined by the dynamic action of the vehicle and the response of the bridge considered as a single system. Figure 1 shows a typical record of the movements that occur during the passage of a vehicle over a bridge. The trace represents the variation in vertical displacement at the middle of the center span of a continuous five-span bridge. The record shows a long-period deflection, which would also occur if the load were acting statically or moving at crawl speed, with a superimposed oscillatory deflection that is related to the natural frequencies of the bridge structure and the vehicle. The ratio between the maximum dynamic and static displacements at a particular point in the structure is defined as the impact factor or dynamic load allowance at that point. After the vehicle leaves the structure, there is a period of free vibration during which the damping capacity of the structure causes the forces to decay to negligible proportions after a few seconds. The damping capacity of a structure is a function of its structural form, the materials of construction, and the support conditions (*10, 11*).

The design of the vehicle's suspension system has an important effect on the magnitude of the loads applied via the tires (*12*). In tests conducted on vehicles with five varieties of mechanical spring suspensions, it was concluded that coupled systems transfer loading between the axles, which can result in increased dynamic axle loading (*13*). The stiffness of the tire also has a significant effect on the fluctuations of dynamic wheel load (*14, 15*). Consequently, although the static deflection increases with the weight of the vehicle, the heaviest vehicles do not always produce the largest dynamic forces in structures.

### MEASUREMENTS OF VIBRATIONS IN BRIDGES

The frequencies of traffic-induced vibrations in bridges are usually within the range from 1 to 20 Hz. The largest amplitudes of vibration occur when the frequencies of the vehicle and the bridge are the same. Measurements of dynamic response of both vehicles and structures were carried out in Ontario (*16, 17*). Most modern heavy vehicles were found to have a natural frequency within the range 2 to 5 Hz. Measurements of impact factors on bridges having a fundamental frequency of vibration within the range of 2 to 5 Hz varied between 27 and 87 percent. Two bridges with fundamental frequencies outside this range, one of 1.6 Hz and the other 5.8 Hz, had impact factors of 10 percent, thus illustrating the resonance effect between vehicle and structure, which produces large dynamic loads. Similar measurements

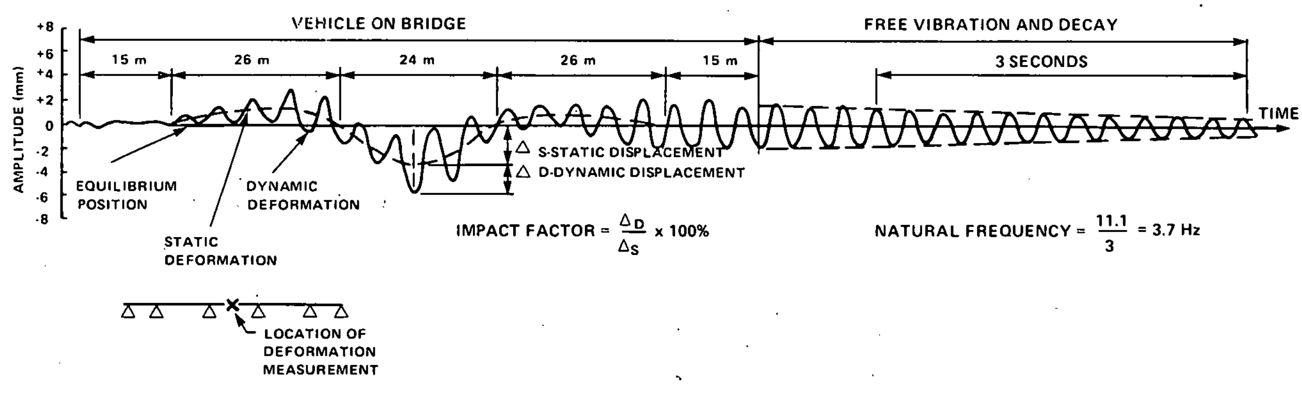


FIGURE 1 Typical displacement-time trace for a vehicle crossing a continuous five-span bridge (*16*).

in England showed the natural frequency of most vehicles to be in the range of 1 to 4 Hz on their suspension systems (including tires) and approximately 8 to 20 Hz for wheel-hop (the motion of the wheel-axle system on the tires) (*18*).

The amount of damping present in a structure greatly affects the magnitude of its response to a vehicle near the resonant frequency (*18*). If the damping capacity is low, large amplitudes of vibration can build up with the successive passage of vehicles across the deck.

It has been shown that maximum dynamic response occurs when the speed of the vehicle is such that the time it takes to cross a span is approximately equal to the fundamental period of vibration of the structure (*12*). Except for very short spans [less than 50 ft (15 m)], vehicle speeds would have to be considerably in excess of legal speeds to produce maximum dynamic loading (*16*). Measurements of the effect of vehicle speed on dynamic load were made in England (*14*) on three bridges with good, average, and poor surface qualities. For the bridge with good surface qualities there was little change in the dynamic component of wheel load. For the bridges with average and poor surface qualities, the dynamic component increased when the speed was increased from 11 to 30 mph (18 to 48 km/h), but there was little change as the speed was further increased to 37 mph (60 km/h). An increase in vehicle speed provides a somewhat greater potential for inducing vibration; however, vehicle speed is not a significant factor in determining response of highway bridges. A larger response may be produced by heavy vehicles accelerating or braking (*18*). Consequently, although a reduction in speed may be imposed in construction zones to increase the level of safety, it will not significantly reduce the effects of traffic-induced vibrations on freshly placed concrete.

The dynamic characteristics of a bridge are represented by all of its modes of vibration. For most simple-span bridges, the bridge vibrates in its fundamental frequency which, for structures of uniform section, can be calculated by substituting $n = 1$ in the beam expression:

$$f_n = \frac{\pi n^2}{2L^2}\sqrt{\frac{EI}{m}} \tag{1}$$

where

$f_n$ = frequency of $n^{th}$ mode of vibration,
$L$ = length of span,
$E$ = equivalent modulus of elasticity of beam,
$I$ = equivalent second moment of area of beam (moment of inertia),
$m$ = mass per unit length, and
$n$ = mode of vibration.

The first five normal modes of vibration for a simply supported beam are illustrated in Figure 2. The natural frequency of these modes increases proportionally in the square integer series (1, 4, 9, 16, etc.), as indicated by expression (1).

The natural frequencies of skewed, simply supported beam-slab bridges can be approximated from the natural frequencies of the equivalent bridge without skew (*19*).

Estimation of the natural frequencies of continuous multispan bridges is more complex and simple methods of analysis for predicting dynamic response are not available. The dominant factor in determining natural frequencies is the ratio of span lengths. A method of estimating the natural frequencies of symmetric, multispan, continuous uniform bridges has been presented in the form of normalized tables (*20*).

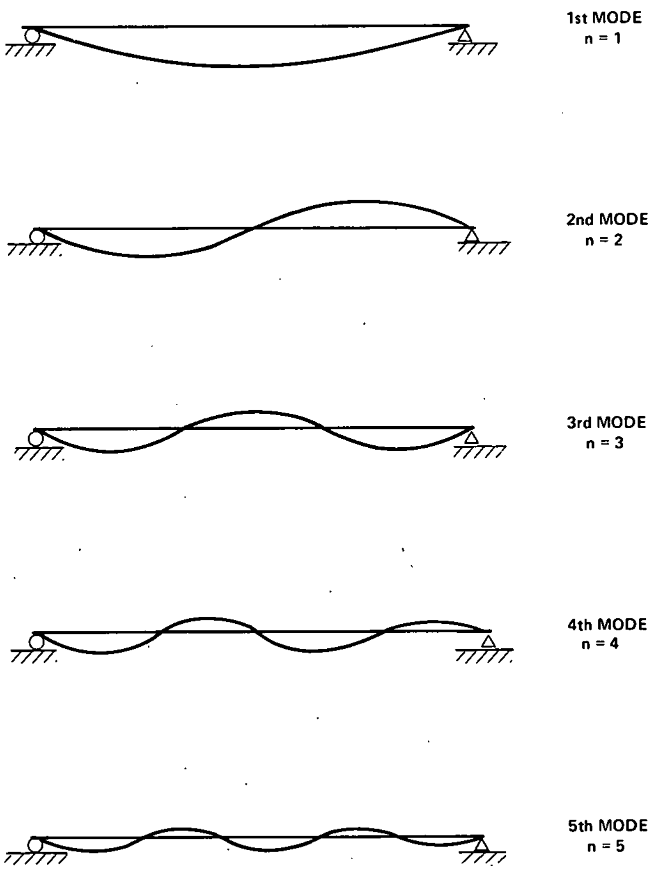


FIGURE 2 Normal modes of vibration for a simply supported beam.

In practice, it is common for the second, third, or higher mode of vibration (or even a combination of modes) to be excited by traffic in multispan bridges, especially in longer structures. As the number of spans increases, the natural frequencies of each mode are more closely grouped together. This increases the probability of resonant vibration so that a vehicle will normally induce a mode of vibration having a frequency close to the natural frequency of the vehicle (*16*). The situation is further complicated by the fact that vehicles in random sequence tend to be out of phase when traversing a bridge such that there is a damping of each other's energy input and the dynamic loading is significantly less than the sum of the dynamic effects of the individual vehicles traversing the structure independently. The response of the interior and exterior beams can also differ in that the vibration of exterior beams may be out of phase with other beams (*21*). The net result is that although estimation of the natural frequency is important in the design of structures to avoid the resonance band (2 to 5 Hz), it is of lesser importance in rehabilitation work except to identify those structures that can be expected to have a particularly lively dynamic response.

In a series of tests by the Transport and Road Research Laboratory in England, deflections and frequencies of vibrations were measured on several structures under test vehicles and normal traffic (*9*). The results are summarized in Table 1 and clearly show the absence of any relationship between static and dynamic deflections (i.e., a wide range in impact factor). The deflections were measured at the center of the instrumented spans and no attempt was made to tune the vehicles to the natural frequencies of the bridges, which were within the range of 2.3 to 5.6 Hz. From the data, the peak particle velocities, which represent the velocities that would be experienced by particles within the bridge deck or pedestrians on the deck, can be calculated from the following relationship, which assumes that the particle motion is sinusoidal:

$$\hat{v} = 2\pi a f \tag{2}$$

where

$\hat{v}$ = peak particle velocity,
$a$ = amplitude of vibration, and
$f$ = frequency of vibration.

The peak particle velocity has been found to provide a more dependable indication of the risk of damage from vibrations than either maximum amplitude or acceleration (*22, 23*). Most of the investigations relating vibration to damage have been concerned with the effect of blasting operations on residential construction. As the most common forms of damage in these buildings are cracking of plaster and breakage of windows, the work is not directly applicable to concrete in bridge decks. However, it is useful in establishing a frame of reference for comparing the peak particle velocities associated with traffic-induced vibrations.

After conducting a review of the literature and an investigation of the vibrations resulting from construction activity, Brown (*23*) found that minor damage (fine cracks in plaster) occurs at a peak particle velocity of 5.4 in. per sec (135 mm per sec) and major damage (fall of plaster, serious cracking) at 7.6 in. per sec (190 mm per sec). A safe limit of 2 in. per sec (50 mm per sec) peak velocity has been recommended to prevent damage to buildings from normal blasting operations (*22, 24*).

Little information exists on acceptable criteria for concrete, especially for fresh and immature concrete. Akins and Dixon (*25*) recommend that construction vibrations be limited to a peak particle velocity of 0.2 in. per sec (5 mm per sec) for concrete less than 24 hr old, 2 in. per sec (50 mm per sec) for concrete 24 hr to 7 days old, and 4 in. per sec (100 mm per sec) for concrete older than 7 days. The authors state that the recommendations, which are directed primarily at the control of blasting operations, are conservative.

Although the concept of peak particle velocity has not been applied to concrete in bridge-deck repairs, it is interesting to note that the peak particle velocities given in Table 1 exceed the maximum velocity recommended for fresh concrete (*25*) but are considerably less than the safe values recommended for concrete older than 24 hr.

## HUMAN SENSITIVITY TO VIBRATIONS

The tolerance and endurance levels of human beings to vibration are primarily of interest in developing design criteria for structures and in assessing the effects of traffic or construction operations on nearby places of occupancy. For this report, an understanding of human sensitivity to vibrations is necessary to better assess the relevance of statements made by field personnel that certain structures were subject to considerable traffic-induced vibrations during repair.

The human body is a dynamic system capable of sensing very small levels of vibration (*18*). Most of the data correlating the reactions of individuals to various levels of vibrations have been developed for buildings. Table 2 gives typical sensitivity levels that have been defined by several researchers (*26–28*) and includes the results of tests undertaken by the Transport and Road Research Laboratory (*18*) to examine the effects of short-term vibrations on pedestrians

TABLE 1
RESULTS OF TESTS ON BRIDGES BY THE TRANSPORT AND ROAD RESEARCH LABORATORY (*9*)

| Bridge No. | Max. Static Deflection in. | Max. Static Deflection mm | Max. Dynamic Deflection in. | Max. Dynamic Deflection mm | Impact Factor % | Frequency of Dynamic Deflection, Hz | Peak Particle Velocity in./s | Peak Particle Velocity mm/s |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.063 | 1.6 | 0.024 | 0.6 | 38 | 4.2 | 0.63 | 16 |
| 2 | 0.063 | 1.6 | 0.028 | 0.7 | 44 | 4.4 | 0.75 | 19 |
| 3 | 0.035 | 0.9 | 0.035 | 0.9 | 100 | 3.8 | 0.87 | 22 |
| 4[a] | 0.035 | 0.9 | 0.016 | 0.4 | 46 | 3.8 | 0.39 | 10 |
| 5 | 0.039 | 1.0 | 0.020 | 0.5 | 51 | 2.3 | 0.28 | 7 |
| 6 | 0.008 | 0.2 | 0.004 | 0.1 | 50 | 4.9 | 0.12 | 3 |
| 7 | 0.012 | 0.3 | 0.008 | 0.2 | 67 | 5.6 | 0.28 | 7 |
| 8 | 0.102 | 2.6 | 0.039 | 1.0 | 38 | 3.0 | 0.75 | 19 |

[a] Bridge No. 4 is the same as Bridge No. 3 after resurfacing.

TABLE 2
HUMAN REACTION TO VARIOUS LEVELS OF VIBRATION

| Peak Particle Velocity | | |
|---|---|---|
| in./sec | mm/sec | Human Reaction |
| 0 - 0.006 | 0 - 0.15 | Imperceptible |
| 0.006 - 0.012 | 0.15 - 0.3 | Threshold of perception |
| 0.08 | 2.0 | Vibrations perceptible |
| 0.1 | 2.5 | Level at which continuous vibrations begin to annoy people |
| 0.2 | 5.0 | Level at which short-term vibrations begin to annoy people, e.g., pedestrians standing on bridges |
| 0.4 - 0.6 | 10 - 15 | Vibrations considered unpleasant by people subjected to continuous vibrations and unacceptable to some people walking on bridges |

on bridges. Vibrations in excess of 0.2 in. per sec (5 mm per sec) were found to be unacceptable to some pedestrians standing on a bridge. The tolerance level decreased from approximately 1 in. per sec (25 mm per sec) at 1 Hz to 0.4 in. per sec (10 mm per sec) at 10 Hz for pedestrians walking. These levels are significantly less than those known to cause damage in hardened concrete.

The extreme sensitivity of the human body to vibration tends to exaggerate personal reactions and makes individual assessment of levels of vibration unreliable. For example, it is not uncommon for individuals to differ by an order of magnitude in estimating the same vibration (*9*). It has been observed that once a person feels a vibration and becomes convinced of the potential for damage, no amount of quantitative data will persuade that person otherwise (*25, 28, 29*). The human body is unreliable for measuring vibrations: thus subjective assessments of the amount of vibration induced by traffic on a bridge undergoing repair or widening should be treated with caution.

## SUMMATION

Vehicles cause bridges to vibrate when the vehicle receives an initial disturbance, such as from passage over an expansion joint or roughness in the approach pavement or the deck surface. The nature of the vibration is the result of the dynamic interaction of the vehicle and the response of the bridge. The largest amplitudes of vibration occur when the natural frequencies of the vehicle and the bridge are the same, usually within the range of 2 to 5 Hz. Vehicle velocity is not a significant factor in determining the amplitude of vibration.

The peak particle velocities associated with traffic-induced vibrations exceed one limit that has been suggested for fresh concrete subjected to vibrations from blasting operations but are considerably less than the criteria suggested for concrete older than 24 hr.

The human body is extremely sensitive to the presence of vibration but unreliable in estimating the magnitude of vibrations.

CHAPTER THREE

# CONCRETE SUBJECTED TO VIBRATION

## CONSOLIDATION OF CONCRETE BY VIBRATION

The consolidation of concrete is discussed here to explain what happens to fresh concrete when it is disturbed by vibrations and to compare the frequencies and forces exerted by vibrators with traffic-induced vibrations on fresh concrete.

The consolidation of concrete to its minimum practical volume through the elimination of all voids except those intentionally included to improve durability (entrained air) improves all the important properties of concrete including strength, impermeability and resistance to abrasion, freezing, and thawing and attack and penetration by aggressive liquids. In reinforced concrete, bond to reinforcement is improved (*30*). It should be noted that the quality of concrete is not improved by vibration per se but by reducing the porosity of the concrete and by permitting the placement of a low water-cement ratio concrete (*31*).

For a given concrete, there is an optimum combination of water content and compactive effort that will produce the greatest improvement in the quality of the concrete. If the concrete is too dry for the compactive effort being provided, quality decreases. If too much water is added, the concrete is easily compacted; however, the quality of the concrete decreases as the water-cement ratio increases. Increasing the sand content of the concrete mixture also improves workability, but also increases cost and requires an increase in water content. Water-reducing admixtures, including high-range water-reducers or superplasticizers, are also used to improve workability. In addition to improving durability, air entrainment reduces the tendency of the mixture to segregate and allow a slight reduction in water content.

Unconsolidated concrete consists of a mass of separate mortar-coated particles that resist consolidation because of internal friction and interference, especially among the larger particles. Consolidation by vibration can be visualized as a two-stage process (*32, 33*). When vibration is applied, the rapid vibratory impulses reduce the internal friction and permit consolidation of the mass, largely by gravitational forces. This first stage of consolidation eliminates honeycombing, but the mortar still contains numerous entrapped air bubbles that occupy several percent by volume of the concrete. In the second stage of consolidation, pressure waves from the vibrator are transmitted through the mortar, and the entrapped air voids, because they are buoyant, rise to the surface and escape. For a given concrete mixture, the degree of consolidation is determined by the amplitude of vibration, the total number of vibrations, and the force exerted on the concrete (*34*). For rotary vibrators, the force is determined by the mass, amplitude, and frequency of the eccentric mass in the vibrator. The number of vibrations transmitted to the concrete is the product of the frequency of the vibrator and the time of application. A more detailed discussion of the factors affecting consolidation of concrete is presented in NCHRP *Synthesis of Highway Practice 44* (*30*) and the report of ACI Committee 309 (*35*).

The recommended frequency for internal vibrators ranges from 170 to 250 Hz for small-diameter vibrators and from 90 to 140 Hz for the large-diameter vibrators used in mass concrete. The recommended frequency for the consolidation of stiff plastic mixtures used in general construction is 130 to 200 Hz (*36*); 170 Hz has been suggested as close to the optimum frequency (*37*). This corresponds to a peak particle velocity of 25 to 50 in. per sec (635 to 1270 mm per sec) for most commercial vibrators. Most electrically driven models operate at 60 Hz, the same frequency as commercial electric power. Surface vibrators and vibrating tables usually operate within the range of 50 to 100 Hz. Shock tables used for consolidating precast elements made from low-slump concrete operate in the range of 2.5 to 4 drops per sec and the free fall is from 0.125 to 0.5 in. (3 to 13 mm) (*36*).

Undervibration is far more common than overvibration. Normal-weight concretes that are well proportioned are not susceptible to overvibration (*36*). The most widely expressed concern about overvibration is segregation of the components of the mixture. The lighter components (water and cement paste) migrate upward; the denser coarse aggregate particles move downward. Overvibration of an excessively wet mixture results in a zone of high water-cement ratio paste or mortar at the surface of the concrete. The layer contains no coarse aggregate and, in air-entrained concrete, may have a frothy appearance. This zone is weak, porous, and of low durability. The tendency to segregate increases with an increase in the difference between the density of the mortar and the coarse aggregate (*31*). In the absence of segregation, loss of most of the entrained air by overvibration is not a serious problem. Because vibration has little effect on the small entrained air bubbles, resistance to freezing and thawing is not significantly affected provided that the concrete originally contained an adequate air void system (*38*).

## DELAYED VIBRATION AND REVIBRATION

Revibration is the process of applying vibration to plastic and partially hardened concrete that has previously been properly consolidated by vibration. Delayed vibration is the term applied to the same process when the concrete has been previously compacted by other means such as rodding of a fluid mixture (*39*) and thus is of little practical significance.

There has been a widely held view that once concrete is placed, compacted, and finished, it should not be disturbed again until it gains sufficient initial strength. It is precisely this viewpoint that has caused concern about maintaining traffic on bridge decks during concrete placement operations. However, it should be recognized that there are several other common situations in which concrete is revibrated unintentionally. Revibration often occurs when concrete is placed in layers, when the vibrator extends into previously placed concrete, and when concrete is subjected to vibrations from pile driving and other construction activities. Not only are these situations not considered harmful, but it is now generally agreed that revibration is beneficial in increasing compressive strength and bond strength. Revibration also releases water trapped under horizontal reinforcing bars and removes additional large air voids (*36, 40*).

Several investigators have reported increases of 10 to 30 percent in the compressive strength of concrete cylinders revibrated 2 to 6 hr after mixing (*40–43*). There was no evidence of segregation in any of the concrete. Tests carried out on cores taken from piles and on cylinders subjected to vibrations from pile-driving operations also showed an increase in compressive strength and led to the conclusion that the vibration of fresh concrete during its settling period is not detrimental (*44, 45*). Revibration of concrete results in an increase in bleeding, a slight increase in elastic modulus, a slight reduction in shrinkage, and no significant change in creep behavior (*43*). However, these findings were based on tests on cylinder specimens in which the concrete was confined during revibration; consequently, the results cannot be applied directly to fresh concrete in bridge decks that are subjected to bending stresses under the action of traffic-induced vibrations.

The time at which concrete is revibrated after mixing has a major influence on the effectiveness of revibration. Revibration within the first few hours after mixing has little influence on the properties of concrete (*43*). It is most effective if conducted just before or after initial set. If revibration is delayed beyond the final set, its effectiveness decreases and eventually becomes insignificant (*31*).

Surface vibration has been shown (*43*) to be an effective method of closing flexural cracks on the surface of concrete as well as subsidence cracks at the level of the top reinforcement if conducted before the penetration resistance of the concrete reaches 60 psi (420 kPa). For most concretes this is 30 min to 1 hr before initial set.

Improvement in the properties of concrete as a result of delayed or repeated vibration has generally been assumed to be caused by a reduction in the porosity of the concrete and the closing of microcracks between the paste and the aggregate because of early shrinkage of the paste (*43, 46*).

## EFFECT OF JARRING AND CONTINUOUS VIBRATION ON FRESH CONCRETE

A number of investigations were undertaken to determine the effect of exposing fresh concrete to jarring or to continuous vibration during the period of setting and strength development.

In 1919 Abrams (*47*) reported that there was a reduction in the compressive strength of concrete exposed to shock loading on a drop table immediately after mixing. A significant increase in compressive strength was reported for concrete that was shock loaded 2 to 4 hr after casting. In tests at the University of California (*48*), strength increases of 13 to 40 percent were measured on concrete subjected to vibrations of 0.55 to 2.6 Hz for periods of 30 to 90 min after mixing. Mortar cubes subjected to varying degrees of vibrations (from gentle vibration to violent vibration) plus tapping for periods of up to 24 hr after mixing hardened satisfactorily and, with one exception, were stronger than those that were not vibrated (*49*). In Sweden (*50*), concrete and mortar specimens exposed to slight vibration and to 1 shock per minute throughout the setting period were found to have significantly higher strengths than control specimens. The increase in strength was greater than could be explained by the reduction in water-cement ratio caused by water expelled from the concrete.

The effect of the vibration from mills used to pulverize coal in a power plant was measured by attaching concrete cylinders to the foundation of the coal mills (*51*). The frequency of vibration varied between 0 and 200 Hz but was approximately 50 Hz for most of the test periods. Concrete compressive strengths were found to increase significantly for cylinders placed on the foundation immediately after casting. For cylinders placed on the foundation at 24-hr intervals up to 3 days after casting, strengths were either increased slightly or unchanged.

In a series of tests to determine the suitability of concrete overlays for the repair of deteriorated bridge decks, a 2-in. (50-mm) thick concrete overlay was placed on a vibrating beam that was subjected to cyclic loading for 48 hr (*52*). The loading was designed to simulate traffic-induced vibrations. The span of the beam was 8 ft (2.4 m), the initial amplitude was 0.022 in. (0.56 mm), and the frequency was 7 Hz. A constant load was maintained so that as the concrete gained strength and the stiffness of the beam increased, the amplitude of vibration decreased. After 24 hr the amplitude was 0.004 in. (0.10 mm). After 48 hr the beam was inspected and found to contain three cracks near mid-span, which were caused by placing the overlay in tension. There was no loss in bond strength between the overlay and the beam. Two cylinders that were cast and cured while attached to the vibrating beam showed considerably higher strengths than the control cylinders.

## EFFECT OF VIBRATION ON REINFORCED CONCRETE

Many engineers have been concerned that vibration of reinforcement may be detrimental to the bond between the steel and concrete, especially if the vibrations are transmitted along the reinforcing bars to concrete that is partially set.

Measurement of bond strength in the series of tests to investigate the effects of coal-mill vibration detected no evidence of bond failure (*51*). The effect of revibration on plain and deformed reinforcing bars has also been reported (*40*). Plain reinforcing bars were placed in 6 by 6 in. (150 by 150 mm) concrete cylinders, which were revibrated 4 hr after casting. The bond between the bars and the concrete appeared to be broken and a small annular space that was visible around the bar at the surface of the concrete was subsequently filled by continued vibration. Bond strengths were 30 to 50 percent higher than control specimens. Similar tests on deformed bars resulted in increases in bond strength of approximately 100 percent for revibration at intervals up to 5 hr after casting. Tests carried out in England (*53*) on specimens containing horizontal reinforcement showed that revibration reduced bond strength. The reduction was slight for revibration within 1 hr after casting and reached a maximum reduction of about 30 percent when the concrete was revibrated 3 hr after casting.

Direct vibration of reinforcement during casting or vibration of reinforcement protruding from partially set concrete was found to have little effect on average bond strength (*53*). The tests on the partially set concrete were more severe than actual practice because the bars were not tied in position and were free not only to vibrate transversely but to slide along their length. The American Concrete Institute (*36*) recommends that concrete that cannot be reached by vibrators, such as in areas of congested reinforcement, be consolidated by vibrating the exposed portions of the reinforcing bars. Careful examination of hardened concrete consolidated in this way has not revealed any detrimental effects.

### SUMMATION

The consolidation of concrete reduces its porosity and improves all its important properties. The frequency of vibration and peak particle velocities of most commercial vibrators are at least an order of magnitude greater than those associated with traffic-induced vibrations in bridge decks.

Several laboratory investigations have shown that delayed vibration, revibration, and vibration throughout the period of setting and early strength development have no detrimental effect on concrete. In most of the tests, the concrete was confined in cylinder or cube specimens during the period of vibration, and the results are not directly applicable to concrete placed in bridge decks and subjected to vibrations by traffic. The studies do show that well-proportioned concrete is resistant to damage and loss of bond with embedded reinforcement as a result of vibration of fresh and immature concrete. Extrapolation of the results is difficult, however, and emphasis must be placed on the results of field tests and those studies that simulate field conditions to analyze the effect of traffic-induced vibrations on bridge-deck concrete.

CHAPTER FOUR

# PARTIAL-DEPTH REPAIRS AND BRIDGE-DECK OVERLAYS

### THE POTENTIAL PROBLEM FROM TRAFFIC-INDUCED VIBRATIONS

Many highway engineers and others have expressed the opinion that traffic-induced vibrations have caused defects in freshly placed concrete. The following is a scenario of what might be expected to happen to concrete placed in a partial-depth repair or overlay on a bridge deck. It is intended to demonstrate most of the concerns and negative views of the possible effects of traffic on the performance of the concrete.

> *When concrete is placed in a partial-depth repair or a concrete overlay, it is in a fluid state and adapts readily to the vibrations and deflections caused by traffic on the traveled portion of the deck. In the hydration process, the concrete gradually changes from plastic to solid. Particles that initially were free to move relative to each other develop resistance to movement and broken bonds may not heal. It is at this stage in the life of the concrete, around the time of initial set, that it is most vulnerable to damage by vibrations. Cracks may occur and bonding deficiencies develop with any reinforcing steel. The presence of cracks may substantially reduce the service life of the overlay by contributing to debonding and permitting deicing chemicals to reach the reinforcing steel. The continual flexing may cause segregation of the mix and may impair the development of bond between the overlay and the existing deck. Jarring and vibration may impair the riding quality of the deck by causing the concrete to flow on decks with steep gradients or cross-slopes. Differential consolidation may occur in concrete of different thickness, as in the case of adjacent areas where extensive concrete removal was required and where it was not.*

### PARTIAL-DEPTH PATCH REPAIRS

Although construction techniques may differ somewhat, concrete placed in a partial-depth repair that extends over only part of a deck slab is in all other ways the same as concrete placed in an overlay. Specifically, it is subjected to the same traffic-induced vibrations at the time of placement and to the same service environment.

In preparing the deck, it is usual first to sawcut the edge of the patch to eliminate feather edges. It is preferable to incline the saw blade to provide a keyed patch (*54, 55*). Unsound concrete is removed by hammers. Sand or water blasting is desirable but is sometimes omitted. Concrete may be often mixed on site or a proprietary patching material may be used (*56*). Depending on the size of the patch, the concrete is often finished by hand.

The effect of traffic-induced vibrations on partial-depth repairs has not been evaluated. It is doubtful that such an investigation is warranted because usually an agency would not consider closing a deck to traffic for the purpose of placing concrete and the consequences of failure of the patch usually are not serious. Patches are generally temporary (*54, 57*) and placed under difficult conditions where the primary objective is to open the deck to traffic as quickly as possible.

## CONCRETE OVERLAYS

### Types and Applications

Several different types of concrete have been used as concrete overlays including low-slump concrete, latex-modified concrete, conventional quality portland cement concrete, fiber-reinforced concrete, internally sealed concrete, and polymer concrete (*54*). Low-slump and latex-modified concrete overlays are by far the most common. With the exception of conventional quality concrete, installations of the other types of concrete have been few and can be considered experimental.

A typical low-slump concrete overlay consists of a 2-in. (50-mm) thickness of concrete with a cement content in excess of 800 lb per $yd^3$ (480 kg per $m^3$) and placed at a slump of less than 1 in. (25 mm). Latex-modified concrete consists of conventional portland cement concrete with the addition of a polymer emulsion, or latex, to the mixture. The concrete is placed at a slump of about 6 in. (150 mm). Styrene-butadiene latexes have been used most frequently in bridge deck overlays. The latex imparts good initial workability, durability, and bonding characteristics to the overlay.

Concrete overlays have been applied as the second stage in the construction of new decks, as preventive maintenance on decks that have been open to traffic for a short time but built without a protective system, and in the rehabilitation of deteriorated decks. Although some information on the effect of traffic-induced vibrations can be derived by comparing the performance of overlays on new decks with those placed on existing decks with traffic maintained, a strict comparison is not possible because overlays placed on existing decks are likely to exhibit defects from such causes as continuing corrosion of reinforcing steel or reflection of existing cracks in the deck slab.

### Structural Analysis

An analysis of the load-carrying capacity of the structure during and after application of a concrete overlay must be carried out as part of the engineering activities in the preparation of contract documents. This is particularly important where the traffic-control plan calls for the use of shoulders outside the normal traffic lanes because unbalanced traffic loading may occur on a deteriorated structure and the structure may not have been originally designed for this condition. This structure must also be analyzed for the additional deck load resulting from the application of the concrete overlay.

### Construction Procedures

The essential procedures in applying a low-slump overlay to an existing deteriorated deck are:

1. Scarify the deck surface to remove at least ¼ in. (6 mm).
2. Remove deteriorated concrete by hand chipping.
3. Sand- or water-blast clean the deck surface and the exposed reinforcement.
4. Apply a mortar or cement-paste bonding agent, usually to a dry surface.
5. Place, finish, and texture the low-slump concrete using equipment specifically designed to consolidate stiff concrete mixtures.
6. Wet-cure the concrete for at least 72 hr.

Steps 1 and 2 are omitted for new decks and step 2 is not required in preventive maintenance applications. The concrete is mixed on site, usually in a continuous high-speed mixer. Epoxy bonding agents have been used, but their use is not common.

The surface preparation of a deck before the application of a latex-modified concrete overlay is exactly the same as for low-slump concrete. The principal differences in construction procedures are that the deck is wetted down, conventional finishing equipment is used, and wet-curing and air-drying are required to hydrate the cement and develop the latex film, respectively. Latex-modified and low-slump concretes are designed to satisfy the same requirements for a high-quality concrete overlay. Low-slump concrete is made of conventional materials, but is difficult to place and consolidate and requires specialized equipment because inadequate consolidation results in a porous and poor-quality overlay (*58*). Conversely, latex-modified concrete is made of expensive materials but is easier to place using conventional equipment with only minor modifications. Additional details on the construction of all types of concrete are presented in *NCHRP Synthesis of Highway Practice 57* (*54*).

### Deck Preparation

Methods of deck preparation have been questioned because of the uncertain effect of vibration from concrete-removal operations on immature concrete in other parts of the deck. Some specifications do limit vibrations from concrete-breaking operations by prohibiting concrete removal from a lane adjacent to freshly placed concrete until the concrete reaches a specified age (often 36 hr). Restrictions may also be placed on the weight of jack hammers and on the operating speed of scarifiers or milling machines. The possibility that hammers might strike the reinforcement so that vibrations are transmitted along the bars to the fresh concrete has been a particular concern. The information in Chapter 3 on the consequences of intentionally vibrating exposed reinforcing bars suggests these fears may be unfounded, provided that the bar is not displaced.

Concrete removal can be extensive, especially before applying a concrete overlay to a deck damaged by corrosion of the reinforcing steel (*6*). However, careful deck preparation is of the utmost importance because a clean, sound surface is required before placing concrete in any repair operation. The absolute minimum of concrete to be removed is that which is physically unsound, including all delaminated areas. Some jurisdictions also remove all the concrete to below the level of the top reinforcing steel from areas where the steel is actively corroding, even though the concrete may be physically sound. It is common practice to restrict the size of hammers used to remove concrete from local areas of deterioration after scarifying to prevent damage to the concrete that is not removed. Typically, the size of jackhammers used above the top reinforcing steel is restricted to a maximum of 30 lb (14 kg) and the size of chipping hammers used below is restricted to a maximum of 15 lb (7 kg).

In a study undertaken to measure vibrations from concrete-breaking operations, a comparison among several pieces of equipment was made (*59*). Peak velocity readings were taken adjacent to the impact area to measure the breakup action of each piece of equipment. Scabblers produced a peak velocity of less than 1 in. per sec (25 mm per sec). The peak velocities produced by jackhammers were approximately 2 in. per sec (50 mm per sec) with little difference between 35-lb (16-kg) and 60-lb (27-kg) hammers. (Velocities greater than 10 in. per sec (250 mm per sec) were anticipated and the difference was ascribed to the dissipation of energy as the concrete fractured.)

Blast cleaning, the final stage of deck preparation, is done just before application of the overlay. After blast cleaning it is not uncommon to find numerous particles of aggregate and mortar that have been cracked or fractured by the chipping and scarifying but not removed. There has been debate concerning whether the direction of rotation of the scarifier, i.e., whether the teeth cut upward or downward, affects the amount of damage to remaining concrete, but there is no consensus on this matter. Concern has been expressed that these fractured particles contribute to a weak zone near the surface of the existing deck, as failure of overlays has been observed just below the bond line (*60*).

Common practice is to confine the term *debonding* to failure at the joint between the overlay and the existing deck. A horizontal fracture plane in the existing deck is referred to as a delamination. Where the location of the failure surface is not determined, it is commonly referred to as a hollow plane.

Bond failures and delamination have been reported in condition surveys of structures, the areas increasing with years of service (*61–63*). Local bond failures have been attributed to inadequate sandblasting, which resulted in failure before a deck was opened to traffic (*64*), and to premature drying of the grout (*65*). However, bond failures and delamination have not been extensive, and there is little evidence to justify a change in current procedures, provided that good quality-assurance practices prevail. The possibility of a weakened surface layer resulting in delamination just below the bond line of an overlay can be minimized by removing cracked particles from the deck surface after blast cleaning.

**Performance of Bridge-Deck Overlays**

Numerous surveys of the condition of concrete overlays have been undertaken, but few have addressed the question of the influence of traffic-induced vibrations at the time of construction. Therefore, an indication of the effect of traffic-induced vibrations must be inferred from the data reported. The lack of information in the literature also prompted the brief investigation of the condition of concrete overlays in Minnesota, New York and Ontario (see Appendix B).

Any defects, principally lack of bond and cracking, resulting from traffic-induced vibrations would be expected to be visible in the concrete shortly after placement. In one instance, cracks were observed when the wet-curing was removed (*6*), and observation of core samples revealed that the cracks passed around coarse aggregate particles, indicating they occurred soon after the concrete was placed. The cause of the cracks was not ascertained; however, the cracking appeared to be predominantly in concrete produced by one of the two continuous mixers used for the work.

Plastic shrinkage, which is caused by evaporation of water from the fresh concrete, is a function of the drying conditions on the concrete surface. Evaporation rates are increased by low relative humidity and increased wind speed and temperature. Thin concrete toppings, in which a large surface is exposed to evaporation, are particularly susceptible to plastic shrinkage cracking.

Cracks were observed in latex-modified concrete overlays placed on four structures in Indiana in the fall of 1979 (*66*). One of the structures was new; the remaining three were repaired while traffic was maintained on the structure. Cracks on two of the structures, including the new bridge, were attributed to plastic shrinkage. On the remaining two structures, the cause was less certain because the cracks tended to be concentrated in certain parts of each bridge deck, whereas shrinkage cracks tend to be more uniformly distributed. It was suggested that finishing or texturing procedures may have been a factor.

The effect of climatic conditions at the time of placing was investigated in the laboratory because it was thought that a cold substrate may have contributed to the cracking. Overlays were placed on substrates at room temperature and at 0° F (−18° C) and the surface of the concrete exposed to simulated wind (*67*). Cracks occurred within 5 to 20 min after exposure to wind in excess of 10 mph (16 km/h). Cracks did not occur at wind speeds of less than 10 mph even after exposure to the wind for periods up to 8 hr, whether or not the base was frozen at the time the overlay was applied. The results emphasize the susceptibility of latex-modified concrete to shrinkage cracking if the curing is not applied almost immediately after concrete placement when evaporation rates are high. They also demonstrate that the rate of evaporation would be a more meaningful operational constraint than the limitation of a maximum temperature, often 85° F (27° C), included in many specifications.

Cracking, debonding, and delamination have been reported in surveys of concrete overlays that have been in service for a number of years (*60, 62, 63, 68, 69*). One of the few studies to attempt to determine the effect of traffic-induced vibrations involved the investigation of 132 latex-modified concrete or mortar overlays in Kentucky, Michigan, Ohio and West Virginia (*62*). Each overlay was inspected and any defects recorded. Information on the details of the structure and the procedures used in constructing the overlays was compiled from records. A regression analysis was made to determine which of several variables (including age of overlay, type of structure, traffic volume, and whether the deck was open or closed to traffic during placement of the overlay) had a significant effect on the condition of the overlay. Only years of service after overlay placement was found to be statistically significant at the 5 percent level. Whether the bridge was open or closed to traffic during overlay placement was not found to have a significant effect on the condition of the overlay. Nevertheless conclusion 17 from this study (*62*) states "Bridges that are open to traffic during latex overlay placement generally exhibit a higher degree of surface distress than those that are closed to traffic. Statistically, this increase was found to be insignificant for the sample studied. Thus it would seem unwarranted to require closing decks to traffic during overlay placements. However, it is certainly beneficial to restrict speed or place the overlay at night or at other times when traffic volume is low." The basis of this conclusion is unclear because the effects of speed restrictions and night-placing operations were not studied in the investigation.

The report (*62*), particularly the conclusion cited above, has subsequently been used as the basis for a recommendation by ACI Committee 224 (*70*): "No traffic should be allowed on the deck, if at all possible, when placing LMC (latex modified concrete) overlays, since it is quite possible that transverse tensile cracks and early bond loss of the overlay will be induced by flexing and vibration of the support beams during early curing of the LMC. Otherwise some means of stiffening the supporting beams during construction should be utilized." This recommendation was questioned because it fails to recognize that the original investigation did not establish a significant relationship between overlay distress and maintaining traffic on the deck and did not examine the influence of temporary supports (*71, 72*). The committee subsequently withdrew the recommendation (*73*).

The Pennsylvania Department of Transporation measured bond strengths on cores taken from parallel structures on which latex-modified concrete overlays were placed (B.F. Kotalik, Chief Bridge Engineer, Pennsylvania DOT; *personal communication*). During placement traffic was maintained only on one structure. There was no significant difference between the bond strengths measured on the two sets of cores.

A survey of the performance of latex-modified concrete overlays was also undertaken in South Dakota (*69*). One lane of each of parallel bridges was overlaid between September 30 and October 2, 1976, while traffic was maintained on both structures. The second lane of each bridge was overlaid on June 2 and 3, 1977, using the same materials, mix proportions, and construction practices. Traffic was again maintained on the structures. The concrete placed on September 30, 1976, had numerous cracks, whereas the concrete placed at other times had only a few small cracks. The cracking was attributed to a slightly higher temperature [90° F (32° C)] and wind speed [15 mph (25 km/h)] at the conclusion of the placement on September 30 than that during the other concrete placements. The placements in June 1977 were made during the late evening.

The report (*69*) also gives details of parallel structures on I-29 over the Big Sioux River between South Dakota and Iowa that were rehabilitated by application of latex-modified concrete overlays between August and October 1976. The bridges were closed to traffic during the repairs. All traffic was routed over the northbound structure while the southbound structure was being repaired. After completion of the southbound bridge, traffic was routed over the structure while the northbound structure was repaired. A few small cracks were visible in the northbound structure. The report also notes the condition of five other latex-modified concrete overlays applied to existing decks and concludes: "Crack patterns on the various decks range from none to extensive and the reasons are not readily discernible. Maintaining traffic on the structure during the construction of the overlay is apparently not a major factor."

During the period 1964–1978, 446 bridge decks were overlaid by the Iowa Department of Transportation. The overall performance of these decks has been satisfactory. Nineteen bridges, overlaid with either low-slump or latex-modified concrete, were the subject of a detailed investigation in 1978 (*60*). The overlays were 5 to 13 yr old at the time of inspection. None of these structures showed evidence of surface distress. Sixteen of the bridges had been included in a survey made in 1974 (*68*). Traffic had been maintained on all the bridges during the repairs.

Hollow areas ranging from 1.2 to 44.9 percent of deck area were located in 17 of the 19 bridges; no hollow areas were detected in the other two structures. Cores showed delamination to have occurred in the original deck concrete in all cases, usually just below the bond line. The overlays were not checked for hollow planes immediately after construction. However, an indication of whether the delaminations were the result of not removing all delaminated concrete at the time of construction was obtained by surveying 25 decks involving work by 6 contractors and 9 inspection crews completed in 1980. No hollow areas were detected. The fact that there were no bond failures at the interface suggests that adequate bond strength was achieved in the presence of traffic at the time of construction. The delaminations were thought to be the result of continuing corrosion of the reinforcing steel or the scarifier creating a plane of weakness in the top of the deck surface (*60*).

Table 3 contains unpublished data on concrete overlays on four bridges near Salina, Kansas. All four bridges were deteriorated extensively when overlaid in 1976 by the low-slump overlay system used in Kansas (*74*). Traffic was detoured from three of the structures during construction (traffic was maintained on Bridge 63). The table presents the results of annual surveys to monitor the performance of the overlays. Because the deck areas differ, cracks have been expressed in terms of length per unit deck area to make comparison possible.

The data are interesting not only because of the inferences that can be made about the effect of traffic, but also because the weakness of using this type of survey to draw firm conclusions is emphasized. Limitations in the accuracy of the data are indicated in the results of the 1978 survey on Bridge 63 where delamination and cracking appear to have been overestimated. The recording of cracks is notoriously

TABLE 3
RESULTS OF SURVEYS OF CONCRETE OVERLAYS IN KANSAS

| Bridge No. | | 1977 | 1978 | 1979 | 1980 |
|---|---|---|---|---|---|
| 63[a] | Delamination, % | 0.03 | 1.5 | 0 | 6.7 |
| | Longitudinal cracks, $mm/m^2$ | 32 | 118 | 102 | 125 |
| | Transverse cracks, $mm/m^2$ | 105 | 390 | 325 | 351 |
| 65[b] | Delamination, % | 0 | 0 | 0 | 0.1 |
| | Longitudinal cracks, $mm/m^2$ | 0 | 62 | 72 | 85 |
| | Transverse cracks, $mm/m^2$ | 0 | 269 | 299 | 361 |
| 66[b] | Delamination, % | 0 | 0 | 0.8 | 1.5 |
| | Longitudinal cracks, $mm/m^2$ | 3 | 121 | 125 | 144 |
| | Transverse cracks, $mm/m^2$ | 26 | 679 | 696 | 725 |
| 77[b] | Delamination, % | 0 | 0 | 0 | 0.9 |
| | Longitudinal cracks, $mm/m^2$ | 0 | 98 | 102 | 115 |
| | Transverse cracks, $mm/m^2$ | 0 | 505 | 531 | 568 |

[a]Traffic maintained. [b]Traffic not maintained.

dependent on the amount of surface moisture on the concrete at the time of observations (*54*). It should also be noted that the effects of the type of structure, positive or negative moment regions in the deck, differences in the condition of the deck before overlay, or differences in the quality of construction were not considered.

After 4 yr, the structure on which traffic was maintained had more delamination but less transverse cracking than the bridges that were free from traffic during the repairs. The amount of longitudinal cracking was about the same for all four bridges. A different conclusion can be drawn from the results of the surveys made 1 yr after overlay placement. The data confirm that the number of defects increases with years of service and that, within a short time after construction, there is no significant difference in the occurrence of surface defects in bridges that were repaired under traffic compared with those from which traffic was detoured.

The observations of bridge-deck overlays in Ontario (Appendix B) support the statements drawn from the data in Table 3.

Most of the overlays observed in New York (Appendix B) were 1 or 2 yr old. The structures were selected to minimize the effects of differences in traffic loading, type of structure, and contractor performance. Few defects were observed and none that could be attributed to traffic on the deck at the time of placing the overlay.

Concern has also been expressed that traffic on the deck at the time of construction can cause slumping of the concrete where the thickness of the concrete is greatest and thereby affect the quality of ride adversely. Measurements of riding quality using a profilometer on concrete overlays placed on bridges in Michigan in 1975 showed a wide variation in smoothness (*75*). All the overlays were placed while traffic was maintained on the structure. In general, latex-modified overlays provided smoother riding characteristics than low-slump concrete overlays. On one large deck on which a low-slump concrete overlay was placed, there was a considerable difference in ride-quality index between lanes placed at different times, suggesting that construction procedures primarily determine the surface profile and that the influence of traffic on the deck is secondary. Subjective assessments of the bridges inspected (Appendix B) revealed no evidence that the quality of ride was affected by traffic-induced vibrations at the time of construction.

## SUMMATION

It is clear from the foregoing discussion that it is not easy to isolate the effects of traffic-induced vibrations from the numerous other factors that may cause defects in concrete overlays. Therefore, it is not surprising that the cause of defects cannot always be explained. A further complicating factor is that possible explanations for cracks visible in overlays shortly after construction, such as substandard materials, improper mixing, or plastic shrinkage resulting from late application of texturing or curing, imply improper construction procedures and inadequate inspection. Because establishing the cause of such cracks is also to assign fault, it is difficult to assemble all the facts from construction records and personnel. Under these circumstances it is easy to visualize how traffic-induced vibrations can become a convenient explanation for defective construction, as neither the contractor nor the inspection staff can be held responsible. The quality and level of inspection are uneven, both within most agencies and from one agency to another. Some areas are fortunate to have stable, well-trained personnel. Others may have a high turnover of staff with the result that inspectors may have minimal training and may be totally unfamiliar with some types of work. This problem is especially serious when the contractor is also inexperienced or not committed to achieving high-quality workmanship.

The only factor that has been shown to have a significant effect on defects identified in condition surveys of concrete overlays in service has been the age of the overlay. In not one survey were traffic-induced vibrations found to have a significant effect on cracking, debonding, delamination, or the ride-quality index; nor has a single case study been documented that shows defects to have been caused by traffic-induced vibrations at the time of construction.

CHAPTER FIVE

# BARRIER WALLS, FULL-DEPTH REPAIRS, WIDENINGS, AND DECK REPLACEMENT

## BARRIER WALLS

Barrier walls that are cast using conventional formwork are unlikely to be adversely affected by traffic-induced vibrations because of the stiffness of the structure at the time the wall is cast and the fact that the concrete is confined within the formwork. Recently there has been a trend toward the construction of barrier walls by slip-forming, which appears to be much more vulnerable to the effects of traffic on the structure at the time of placement. No reports of difficulties in construction or of poor performance have been located in the literature. An informal telephone survey, conducted during this study, of state agencies that have slip-formed barrier walls under traffic found that no additional restrictions are placed on traffic and no adverse effects of traffic-induced vibrations have been identified.

## FULL-DEPTH REPAIRS

The use of full-depth patches to repair local areas of deterioration in bridge decks, as distinct from replacement of the entire deck slab, is not a common procedure. Where isolated areas of full-depth repairs are required in contracts for the installation of concrete overlays, concrete is often placed in the repair area at least 1 day before the overlay is placed. The concrete is usually placed to just above the level of the top reinforcement. This sequence of construction ensures proper compaction in the repair area, simplifies placement of the overlay, and eliminates any problems arising from attempts to properly consolidate widely differing thicknesses of concrete. Where the deck slab has deteriorated to the extent that full-depth repairs are needed, complete slab replacement is often a preferred option to provide additional service life to the structure.

## BRIDGE WIDENING

### The Potential Problem from Traffic-Induced Vibrations

The effect of traffic-induced vibrations on concrete in a bridge widening is much more complex than their effect on a concrete overlay. In addition to being subjected to the same potential problems as concrete in an overlay, concrete in a widening is vulnerable to longitudinal cracking and loss of bond with embedded reinforcement. Transverse cracking of the fresh concrete in the negative moment areas of the deck slab is not of serious concern because the surface curvatures in the longitudinal direction associated with live-load deflections are very small.

As in the case of a concrete overlay on a bridge deck, numerous concerns have been voiced on the possible negative effects of traffic-induced vibrations on concrete in a deck widening. The following scenario expresses these potential effects:

*When a vehicle crosses a bridge, the existing slab deflects. Where the widening is attached, the widening also deflects, but not as much, because of load distribution through diaphragms and deck forms. A typical deflection profile at mid-span is shown in Figure 3. When the concrete is fresh, the particles slide with respect to each other in response to deflections of the formwork. As the concrete stiffens, it develops resistance to deformation and is subjected to tensile stresses. The negative moment is greatest over the most interior beam of the widening and any cracking might be expected over this beam at mid-span.*

*Reinforcing steel or dowel bars extending from the existing deck into the fresh concrete may move with the existing deck and displace plastic concrete. Initially the concrete would be expected to flow back into place, but repeated displacement may cause segregation. As the concrete stiffens, the concrete loses its ability to flow and there is a danger that voids may develop around the bars. The voids would impair bond strength and may result in future deterioration of the concrete. If such voids do develop, they would be expected close to the joint line. Differential movements between the existing deck and the widening may also inhibit the development of bond at the joint line.*

*In addition, the reinforcing steel in the widening is attached to the dowels or lapped bars from the existing deck and is also subjected to the deflections of the existing deck. Although the mat is flexible, it offers resistance to the movement of the fresh concrete. If the plastic concrete, the formwork, and the reinforcing steel vibrate with the same frequency and amplitude, no distress will occur. If relative movement takes place, voids and incipient fracture planes at the level of the steel may be anticipated.*

### Structural Analysis

The structural analysis that must be undertaken to verify the traffic-control plan is not only more complex than required for a deck overlay, but also may present opportunities for mimimizing the effect of traffic-induced vibrations, which are not available during overlay placement. For

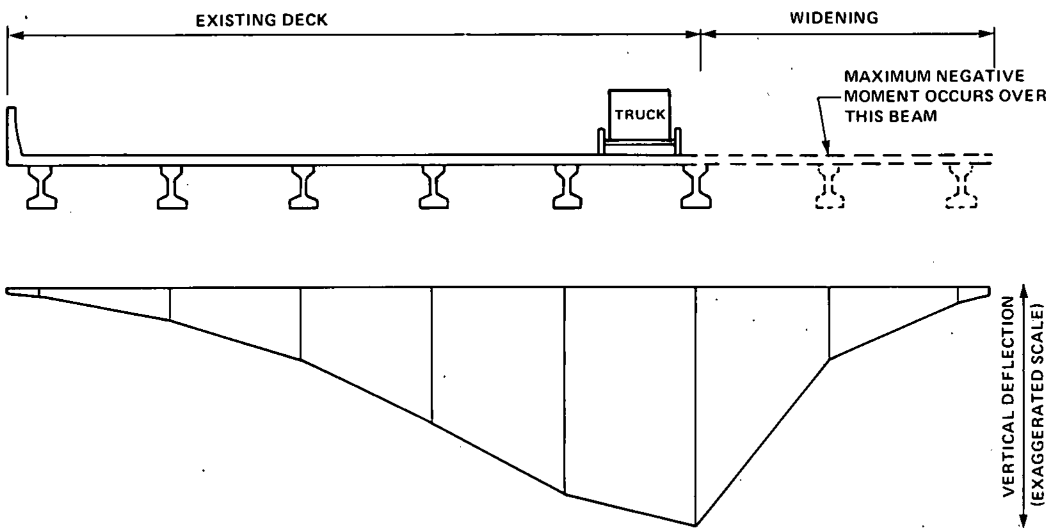


FIGURE 3 Deflection profile at a transverse section of a bridge at mid-span.

example, if a closure pour is to be used, the release of steel diaphragms while the widening is placed will reduce load transfer to the fresh concrete; diaphragms would be reconnected before the closure pour is placed. Also, the use of separate piers for the widening could be investigated. Engineering judgment, type of structure, and site conditions determine where such measures can be used to advantage. In general, where the effect of traffic-induced vibrations can be minimized without greatly affecting the cost of a project, it is prudent to do so, thereby reducing the risk of damage by minimizing the unknown factors.

#### Experience in Michigan

During the 1965 construction season, work was begun on widening 110 spans of 34 structures on I-94 in Michigan. Traffic was maintained on all but two of the structures. Construction procedures did not require placement of a closure pour, and the fresh concrete in the widenings was subjected to the vibrations induced by heavy trucks in the adjacent traffic lane. Temporary shoring was placed in 44 spans in an attempt to reduce the effects of traffic-induced vibrations on the fresh concrete. All the spans were simply supported or cantilevered; none was continuous.

During construction, rippling of the deck surfaces was observed, with troughs visible over the top transverse bars and crests between the bars. The vertical distance between the crests and troughs of the ripples was about ⅛ in. (3 mm). In one of the structures widened under traffic, small fountains of clear water flowed from the surface of the concrete (*76*). Subsequent coring revealed a zone of weak and porous concrete approximately ⅛-in. thick near the level of the top reinforcement.

Ripples of a similar magnitude to those in the bridge widenings occurred during the construction of several new bridges in Michigan at about the same time (*77, 78*). It was observed that, in finishing the decks, coarse aggregate was displaced from above the reinforcement, resulting in an increase in the paste content of the concrete over the bars, which, in turn, would cause greater shrinkage (*78*). Cracks were visible directly over the reinforcement on a number of structures shortly after construction. It was reported that vibration from construction activities on new bridges and from traffic during bridge widenings contributed to the rippling of the deck surfaces.

Also in the mid-1960's, some of the bridges that had been built in the 1950's began to exhibit premature deck deterioration, particularly spalling (*79*). Such deterioration was experienced in Missouri, where it was the subject of an extensive investigation (*80–82*). At that time, the term *fracture plane deterioration* was used to identify the separation of a layer of concrete from the underlying deck slab, before the breakup of the upper layer and the formation of potholes (*81*). The separation is now commonly referred to as a delamination, and the subsequent breakup is called spalling (*54*).

A hypothesis was developed by the Missouri investigators to explain fracture plane deterioration. The central feature of the hypothesis was the existence of a plane (or zone) of weakness built into the deck slab at the time of construction (*81*). It was suggested that rapid drying of the concrete surface, the prevention of bleeding of excess mix water, and the prevention of subsidence of aggregate by the top mat of steel caused the formation of a zone of high-water-content, weak concrete undulating between the top reinforcing bars. Shrinkage cracks over the reinforcement permitted the access of water and deicing chemicals to the reinforcement. Corrosion of the steel and the development of expansive forces around the bars then resulted in a fracture plane that followed the zone of weak concrete.

Reports of fracture plane deterioration in both Missouri (*80, 81*) and Michigan (*79*) led to the explanation of the mechanism of this type of deterioration sometimes being referred to as the Missouri-Michigan hypothesis. This term has not been widely used, however, partly because of changes in terminology and partly because the mechanism of corrosion-induced deterioration in reinforced concrete is now better understood. Several attempts to reproduce the plane of weakness in the laboratories of the Missouri State Highway Department (*81*) and the University of Illinois (*43*) were unsuccessful, even under extreme environmental conditions of elevated temperatures and high winds. Later work has shown that a plane of weakness in the concrete or cracks over the reinforcement is not a prerequisite to the development of spalling (*54*). Deicing chemicals can initiate corrosion of the steel, which ultimately results in spalling, even in good-quality concrete. The time to corrosion increases with an increase in the quality of the concrete (decrease in water-cement ratio), improved degree of consolidation, and an increase in the cover to the reinforcing steel (*58*). However, if a porous zone is present in the concrete, the time to spalling is reduced substantially.

The specifications in use in Michigan in the mid-1960's required a cement content of 564 lb per $yd^3$ (338 kg per $m^3$) and a water-cement ratio of 0.53. It is now recognized that excess water in the mixture was the primary factor causing premature deterioration in bridge decks built during that period (*83*). A specified cover of 1⅝ ± ⅜ in. (40 ± 10 mm) compounded the problem. Limited experiments were undertaken at the Michigan State Highway Commission laboratories in 1979 to investigate the effects of quality of concrete and vibration on the failure of concrete slabs due to the development of internal pressure, as would result from the corrosion of reinforcement. Although the number of tests was insufficient to establish conclusions, the results indicate that a low water-cement ratio, modern-slump mixture is tolerant of vibrations during the setting period. Concrete of higher water content tended to be more susceptible to the effects of vibrations. Bleed-water channels extended to the level of the reinforcement, and there was a greater tendency for the slabs to fail horizontally and at lower pressures than in the moderate-slump concrete.

There is no doubt that local accumulations of water in bridge decks, accentuated by vibration, contributed to the rapid deterioration of some structures in Michigan and Missouri in the mid and late 1960's. Improvements in mixture proportioning and quality-assurance procedures for concrete and an increase in cover (*84*) have reduced the probability of the formation of fracture planes in new decks. These measures, together with the use of such protective treatments as coated reinforcing steel and concrete overlays, have prevented the rapid and widespread deterioration that occurred in some structures in the 1960's.

A survey reported in 1975 (*85*) of the performance of the structures widened in 1965 revealed no significant relationship between the degree of deterioration and the use of temporary shoring during construction. In fact, the spans that were shored showed slightly more deterioration than the unshored spans. It was concluded that other variables, such as concrete quality, cover to the steel, and the location and detail of the splice, have more effect on deck performance than does the use of shoring. The analysis of the results was complicated by the occurrence of a dispute between contractors, which resulted in concrete being hauled over distances as great as 35 miles (56 km), and this may have adversely affected the quality of concrete placed in some structures.

One particular problem that was identified in surveys of widened bridges was that often the fascia beam of the existing deck was designed to have more camber than the other beams. When this beam became an interior beam in the widened structure, it was difficult to achieve the required deck thickness and cover to the reinforcing steel. It was, therefore, recommended that the fascia beam either be lowered at the bearings or used as the fascia beam in the widened structure (*83*).

#### Experience in California

Before 1965 it was the practice in California not to attach a widened deck to the original structure (*86*). This practice was followed because of the ease of construction and to avoid a theoretical overstress in the original exterior girder caused by attaching the widening to the original structure. It should be noted, however, that the overstress condition would only occur if the effects of moment transfer to other girders of the widened structure were neglected. However, because of the difficulty of accurately predicting dead-load deflections, there was a difference in elevation between the surfaces of the new and old decks. The resulting step in the deck surface was hazardous, especially to motorcycles, and vulnerable to spalling by traffic. Consequently, a policy of using attached widenings was adopted in 1965.

Fifty-eight widened structures were studied in 1973 to evaluate the effectiveness of the change in policy (*87*). Most widenings were completed with the placement of a closure pour. The transfer of loads from the widening to the original structure is reduced by increasing the delay between placing concrete in the widening and in the closure. This permits time-dependent deformations to take place in the widening. On precast concrete girders and steel girder widenings, the minimum required waiting time varied between 3 and 15 days. For cast-in-place concrete girder widenings, the formwork was required to be kept in place for a minimum of 10 days and then be removed before placing the closure pour. The longest required waiting period was 60 days after release of falsework. This requirement was stipulated for three structures where large deflections were anticipated.

All the widenings included in the study were found to be performing well and without major structural distress. There was no evidence of overstress in the original exterior girder adjacent to the widenings. It was concluded that short-span bridges could be widened without overstressing the exterior girder even when a closure pour was not used. All noted deficiencies were minor in nature and, in most cases, neither unsightly nor in need of maintenance. The attached widenings were found to provide a smoother riding surface, less maintenance, improved aesthetics, and improved safety as compared with non-attached widenings. Design details that do not provide for the transfer of bending moment, such as a single row of dowels or a keyway, caused minor problems in the form of spalling and separation between the original and widened decks. Consequently, it was recommended that the widened deck be attached by lapping to both the top and bottom transverse steel in the original deck slab. Steel girder bridge widenings had the fewest problems along the longitudinal joint; precast-prestressed concrete, short-span conventionally reinforced concrete "T" girders and concrete box girders had, in order, a greater number of defects.

Widening practice in California has subsequently been modified (*88*) to implement a number of recommendations contained in the 1974 report (*87*). Except for very short spans, where the dead-load deflection is less than ¼ in. (6 mm), the main portion of the widening is constructed and allowed to deflect before placing a closure pour to complete the attachment to the existing structure. Dowels are used only to connect the closure pour to the existing deck slab where the transverse reinforcement cannot be connected by welding or lapping to provide the strength required to transfer moment across the longitudinal joint. Where dowels are used, a double row has been found to perform better than a single row of dowels. Benching into the existing exterior girder as a means of support for the closure pour is not used because cracking usually occurs in the widened deck above the face of the bench.

For precast concrete and steel girders, most of the deflection in the girder is dead-load deflection that occurs when the deck slab of the widening is placed. For this type of structure, the closure pour may be placed as soon as the concrete in the widening has reached sufficient strength that it will not be damaged by construction operations or transfer of load through the closure pour.

For cast-in-place structures, the dead-load deflection continues after the falsework is released. Two alternative sequences of construction allow for a substantial proportion of the ultimate time-dependent deformation of the girders to take place before placing the closure pour. When falsework is not a hazard to traffic, it may be left in place for not less than 28 days and the closure pour placed no sooner than 14 days after removal of the falsework. When the widening is constructed over traffic, it is desirable to remove the falsework as soon as possible; thus it is removed as soon as the concrete in the widening has reached the strength required by the specifications for release of the falsework. The closure pour is placed no sooner than 60 days after the falsework has been released. Where conditions permit, the contractor is given the option of these alternatives.

Most structures are widened while traffic is maintained on the existing structure. In order to minimize the effects of vibrations from traffic on the concrete in the widening, the reinforcing steel and formwork of the widening are isolated from the existing deck. During construction of the closure pour, the reinforcing steel of the new and existing concrete is securely fastened together. Where possible, traffic is routed one lane away from the widening, especially during placement of the concrete.

### Experience on the New Jersey Turnpike

Widening of both the Hackensack River and Passaic River bridges on the New Jersey Turnpike was completed in 1974 (*89*). These structures are both steel girder bridges with lengths of over 1 mile (1.6 km). The work was performed with one lane in each direction closed to traffic, leaving the other two lanes open in each direction. On the Hackensack River Bridge the new girders were preloaded to remove the camber and the permanent connection between the old and new floor beams made before placing the new deck slab. A 6-ft (1.8-m) closure pour was used on the Passaic River Bridge. Concrete was pumped from beneath the bridges. At the time of construction no problems were encountered on either bridge as a result of the effects of traffic-induced vibrations. Subsequent performance of the widenings has been satisfactory.

Since the turnpike was opened in 1952 several deck slabs have been replaced. All the work has been done with traffic maintained on the structures. No detrimental effects from traffic-induced vibrations have been identified (R. F. Zipp, Project Engineer, New Jersey Turnpike Authority; *personal communication*).

### Experience in Texas

In 1979 a survey of 30 bridges that had been widened between 1956 and 1979 was conducted (*90*). Spans varied from 25 to 110 ft (7.6 to 34 m); both simple and continuous-span bridges were evaluated. Traffic was maintained on all the structures during widening and a separate closure pour was not used. In most cases, the speed of traffic was restricted, but there were no weight restrictions. The sample included bridges with steel, reinforced concrete, and prestressed concrete girders. Some of the bridges on the Interstate system were originally parallel bridges; these were widened to form a single deck slab by additions to the outsides of both bridges and by infilling the deck between the bridges using a three-stage construction procedure.

Four different widening details were used (see Figure 4). Only one bridge had an open joint of the type shown in Figure 4*a*. Spalling was observed along the edges of the longitudinal joint as a result of differences in the deflection of the widening and the original bridge. For all the other widenings, reinforcement was carried through the joint. The majority of the widenings were of the type shown in Figure 4*c* or 4*d*, with only a few short-span bridges being widened as shown in Figure 4*b*. Few instances of distress were observed during visual examination and none that could definitely be attributed to maintaining traffic during construction. In a few bridges a narrow crack was visible along the construction joint. Except for these cracks, the crack pattern in the widening was similar to that in other parts of the deck. Most of the wider cracks were oriented perpendicular to traffic, although maximum negative bending was anticipated over the most interior new beam. No differences in the performance of the details shown in Figures 4*c* and 4*d* were observed to indicate a preference for one detail over the other. This is contrary to the experience in California where cracking was found above the face of the beam when the detail shown in Figure 4*d* was used (*88*).

A total of 109 cores were taken from nine of the structures. The locations of the cores were selected to (a) sample concrete on which traffic-induced vibrations had a maximum effect, such as at mid-span adjacent to the joint line, and (b) sample concrete that was relatively undisturbed by traffic, such as at or near piers. The cores were analyzed for cracks and evidence of loss of bond and were tested for strength and

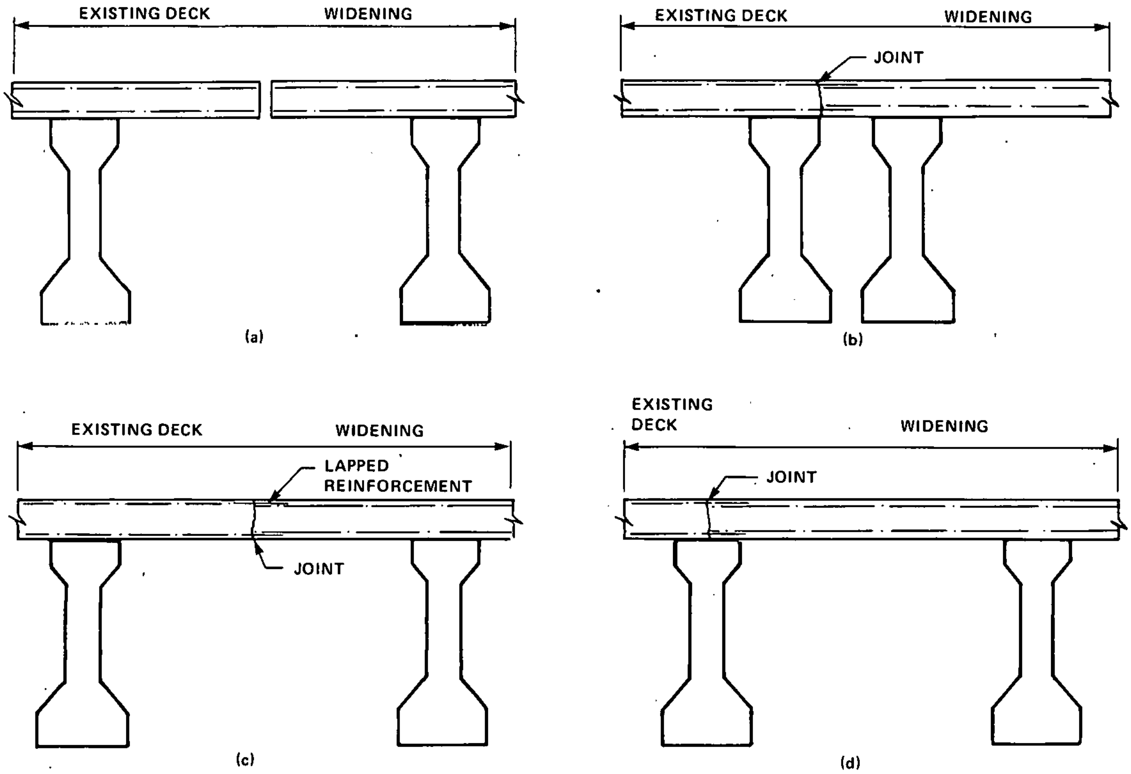


FIGURE 4 Details of bridge widenings in Texas.

sonic pulse velocity. Numerous microscopic cracks were found in the cores, but there was no significant difference between the cores taken from areas where the concrete was disturbed by traffic and those taken from areas that were undisturbed.

Five cores of 23 taken from parallel structures showed evidence of relative movement between the reinforcing steel and the concrete. All five cores were taken at or near the joint line. Voids were visible around bars in two of the cores and dye tests indicated poor bond in the other three. Cracks were visible on the surface of one core and the concrete appeared to have been disturbed in the plastic state. The damage was attributed to an unusual reinforcing detail (see Figure 5), in which reinforcing bars extending from the old concrete were bent 90 degrees in the new concrete . These defects were not present around dowels that were not bent into the new concrete. There was no evidence of lack of bond or traffic-induced distress in any of the cores from the other structures included in the survey.

Deflections and vibrations were measured on nine bridges selected to represent the range of structural type and span size included in the overall investigation. On three of the bridges, measurements were taken before, during, and for 24 hr after concrete was placed in the widening. Measurements were also made to determine if there was any relative movement between the reinforcing steel and the concrete.

Results of the field tests are given in Table 4. The maximum differential deflection reported is the relative deflection between the existing edge beam of the old concrete deck and

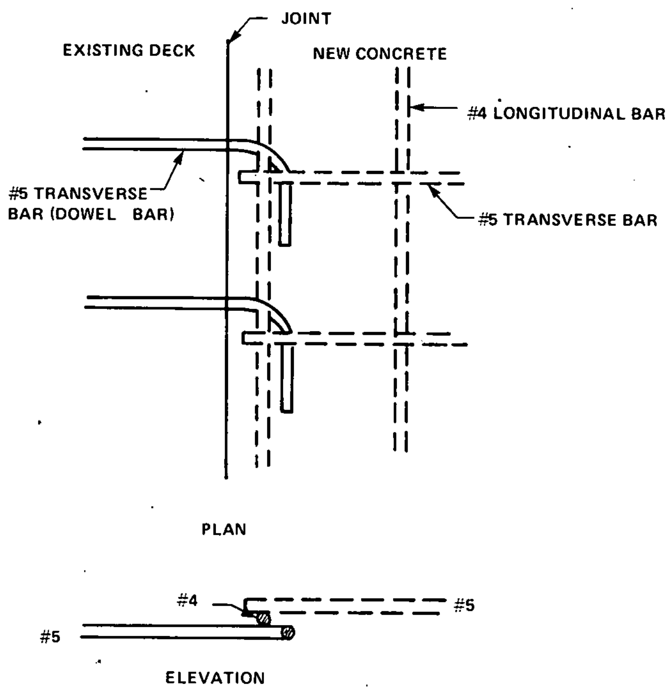


FIGURE 5 Reinforcing detail at joint line.

TABLE 4
RESULTS OF FIELD TESTS ON WIDENED BRIDGES IN TEXAS

| Bridge No. | Natural Frequency Hz | Maximum Differential Deflection in. | mm | Maximum Curvature $10^{-5}$ in.$^{-1}$ | $\mu m^{-1}$ |
|---|---|---|---|---|---|
| 1 | 5 | 0.032 | 0.81 | 0.22 | 0.055 |
| 2 | 5 | 0.041 | 1.04 | 0.33 | 0.083 |
| 3 | 5 | 0.120 | 3.05 | 0.25 | 0.064 |
| 4 | 4 | 0.060 | 1.52 | 0.84 | 0.213 |
| 5 | 10 | 0.032 | 0.81 | 0.23 | 0.058 |
| 6 | 5 | 0.058 | 1.47 | 0.83 | 0.221 |
| 7 | 4.5 | 0.058 | 1.47 | 0.69 | 0.175 |
| 8 | 6 | 0.040 | 1.02 | 1.14 | 0.290 |
| 9 | 3.5 | - | - | - | - |

the first new beam in the widening. The maximum curvatures in the transverse direction were calculated from the measurement of the deflected cross section of the bridge. No relative movement between the reinforcing steel and the plastic concrete was recorded. The frequency and amplitude of the instrumented points in the bars and the formwork were the same at all times.

It was possible to measure a change in natural frequency during construction of the widening on only one bridge. For this structure the natural frequency was 5 Hz before widening, 3.5 Hz directly after placing the concrete, and 5 Hz about 12 hr after casting. As noted in Chapter 2, frequency is proportional to the stiffness of the member and inversely proportional to mass. With the added mass of the fresh concrete, the frequency is decreased, but, as the concrete hardens, the frequency increases with the increase in the stiffness of the concrete and the development of composite action.

A series of laboratory tests were undertaken using beam specimens to simulate a 1-ft (0.3-m) strip of bridge deck. The tests were conducted to further investigate the effects of vibrations on bond strength and to determine under what conditions simulated traffic loads would cause the concrete to crack. The specimens were supported on flexible supports that were designed to provide approximately the same curvature under test conditions as was measured in the field. The beams were dynamically loaded in flexure from the time concrete was placed in the forms. In four tests the beams were loaded at 5-min intervals; in the fifth test a continuous vibration at a frequency of 6 Hz was superimposed on the intermittent loading.

Flexural cracks developed as a result of deflection of the formwork supporting the fresh concrete. The curvatures measured in the beams at approximately 30 min after casting and at about 5 hr, by which time the concrete had taken its initial set, are given in Table 5. The table also lists the maximum crack widths and the time after casting when the first crack was detected. It was found that the extent and severity of cracking were a function of the surface curvature of the plastic concrete.

The maximum curvature of the concrete decreased with age. The relationship between curvature and the properties of the beam, assuming the simple theory of bending is applicable, is given by the expression:

$$\rho = \frac{1}{R} = \frac{M}{EI} = \frac{\sigma}{Ey} = \frac{\epsilon}{y} \tag{3}$$

where

$\sigma$ = curvature,
$R$ = radius of curvature,
$M$ = bending moment,
$E$ = modulus of elasticity,
$I$ = second moment of area (moment of inertia),
$y$ = distance from neutral axis to extreme fiber,
$\sigma$ = stress in extreme fiber, and
$\epsilon$ = strain in extreme fiber.

As the concrete develops strength, the stiffness (*EI*) of the beam increases and the curvature decreases. Because the cracks developed approximately 4 hr after casting and the curvature decreases with age, fresh concrete is able to tolerate a greater curvature without cracking than is concrete that has stiffened. Other investigators have found that concrete that has a penetration resistance of less than 15 psi (100 kPa) is not easily cracked (*43*). The presence of continuous vibration (beam No. 4 in Table 5) was found to increase the curvature and the amount of cracking. It was not possible to measure any relative movement between the steel and the concrete, but cores taken from the beams showed some blurred imprints on bars that were designed to simulate tie bars between new and old concrete. This indicates that some slight movement may have occurred, but there was no evidence of any bonding problems.

A concrete surface curvature of approximately $0.36 \times 10^{-4}$ in.$^{-1}$ (0.91 $\mu m^{-1}$) was found to be necessary for cracking to develop in the 7-in. (180-mm) thick beams. In an earlier laboratory study at the University of Illinois (*43*), beams containing fresh concrete were statically loaded to simulate deflection of the formwork and to determine the curvature necessary to cause cracking. The results are given in Table 6. Within 2 to 4½ hr after mixing, the time at which the concrete was deflected had little effect on crack width and spacing. Deflection after 4½ hr resulted in deeper cracks, but the maximum crack width was not changed significantly.

The beams used in the University of Illinois study were 6-in. (150-mm) thick. For the same surface strain, curvature is inversely proportional to the distance of the surface from the neutral axis of the beam. Therefore, the same curvature will produce a greater surface strain in a deeper beam than in a shallower beam. For comparative purposes, the curvature measured in the shallower beam must be reduced by the ratio of the depth of the beams. If all the data are adjusted for a member thickness of 7¾ in. (200 mm) for comparison with the field measurements, the University of Illinois data indicated a first cracking under static load at a curvature of $3.9 \times 10^{-4}$ in.$^{-1}$ (9.8 $\mu m^{-1}$). In the laboratory study at Texas A & M University (*90*), cracking was observed at a curvature of $0.33 \times 10^{-4}$ in.$^{-1}$ (0.83 $\mu m^{-1}$), which is an order of magnitude less than that in the University of Illinois study and indicates the effect of the dynamic loading used in the

TABLE 5
RESULTS OF LABORATORY TESTS ON SIMULATED BRIDGE DECKS
(*91*)

| Beam No. | Age After Casting (hr | min) | Curvature $10^{-5}$ in.$^{-1}$ | $\mu m^{-1}$ | Maximum Crack Width in. | mm | Approximate time to First Cracking hr | min |
|---|---|---|---|---|---|---|---|---|
| 1[a] | 00 | 30 | 6.5 | 1.65 | 0.005 | 0.12 | 4 | 30 |
| 2 | 00 | 40 | 5.4 | 1.48 | 0.004 | 0.10 | 4 | 25 |
| | 5 | 30 | 4.3 | 1.10 | | | | |
| 3 | 00 | 35 | 5.6 | 1.41 | 0.003 | 0.08 | 4 | 00 |
| | 5 | 48 | 2.6 | 0.65 | | | | |
| 4 | 00 | 36 | 6.1 | 1.55 | 0.006 | 0.15 | 3 | 45 |
| | 5 | 47 | 4.5 | 1.15 | | | | |
| 5 | 00 | 30 | 3.6 | 0.91 | 0.003 | 0.08 | 10 | 30 |
| | 11 | 34 | 4.4 | 1.12 | | | | |

[a]Unreinforced beam. Once cracks formed, all rotation occurred at the cracks, which acted as hinges.

TABLE 6
SURFACE CURVATURE NECESSARY TO CAUSE CRACKING (*43*)

| Cracking | Maximum Crack Width in. | mm | Curvature $10^{-4}$ in.$^{-1}$ | $\mu m^{-1}$ |
|---|---|---|---|---|
| Slight | 0.001 - 0.002 | 0.02 - 0.27 | 5 | 13 |
| Medium | 0.005 - 0.010 | 0.13 - 0.25 | 10 | 25 |
| Severe | 0.030 - 0.050 | 0.76 - 1.27 | 25 | 64 |

latter study. The maximum curvature measured in the field was $0.114 \times 10^{-4}$ in.$^{-1}$ (0.29 $\mu m^{-1}$). This is about one third of the curvature that caused cracking in the laboratory and provides most of the explanation for the absence of longitudinal cracks in the visual survey portion of the investigation. After analysis of all the field and laboratory data, the investigators concluded (*90*): "Vibrations caused by normal bridge traffic have no detrimental effect on the concrete, the reinforcing steel, nor the interaction between the reinforcing steel and the concrete."

### Experience in Georgia

In 1979 a research study was initiated by the Georgia Department of Transportation to (a) evaluate the effectiveness of the existing practice of using closure pours, (b) determine the feasibility of eliminating closure pours in the widening of some types of bridges, and (c) determine if traffic should be allowed to use all lanes of an existing bridge undergoing widening.

The normal practice used in Georgia for bridge widening is as follows:

1. Place a temporary barrier on the existing bridge adjacent to the exterior girder.
2. Remove the existing curbs and handrail and cut the existing slab, taking care to leave the existing bar reinforcement.
3. Construct a new bridge parallel to the existing bridge separated only by a narrow closure strip approximately 2 to 4 ft. (0.6 to 1.2 m) wide.
4. After the concrete in the new bridge gains sufficient strength, keep all traffic off the existing bridge or narrow traffic to one lane with a greatly reduced speed to prevent severe vibrations for a period of 24 hr. Pour the closure strip using high-early-strength concrete.
5. After the concrete in the closure strip gains sufficient strength (usually after about 24 hr), remove the temporary barrier and open widened bridge to traffic.

In the course of the investigation, reinforced concrete specimens were prepared by bolting two concrete blocks, each 24 by 36 by 7-in. (600 by 910 by 180 mm) deep, to each side of the closure pour on two bridges. The blocks were located at mid-span such that the concrete in the specimen would be subjected to the maximum amplitude of traffic-induced vibrations. Three reinforcing bars projected from each block into the area of the closure pour and were tied with wire in the same way as conventional lapped bars. The arrangement of the test is shown in Figure 6. The concrete was placed in the closure pour and then in the test specimen. Bond between the test specimen and the concrete in the closure pour was prevented by a polyethylene sheet. Traffic was maintained on both structures throughout construction. The relative movement between the old deck and the closure pour was measured to be less than 0.01 in. (0.25 mm). A control specimen having the same dimensions as the specimen cast on the bridge was prepared from the same concrete mixture but cured elsewhere on the construction site where it was not subjected to the effects of traffic.

The specimens were cured on site for several days before removal to the moisture room. Each specimen was cut into six pieces so that each piece contained a reinforcing bar

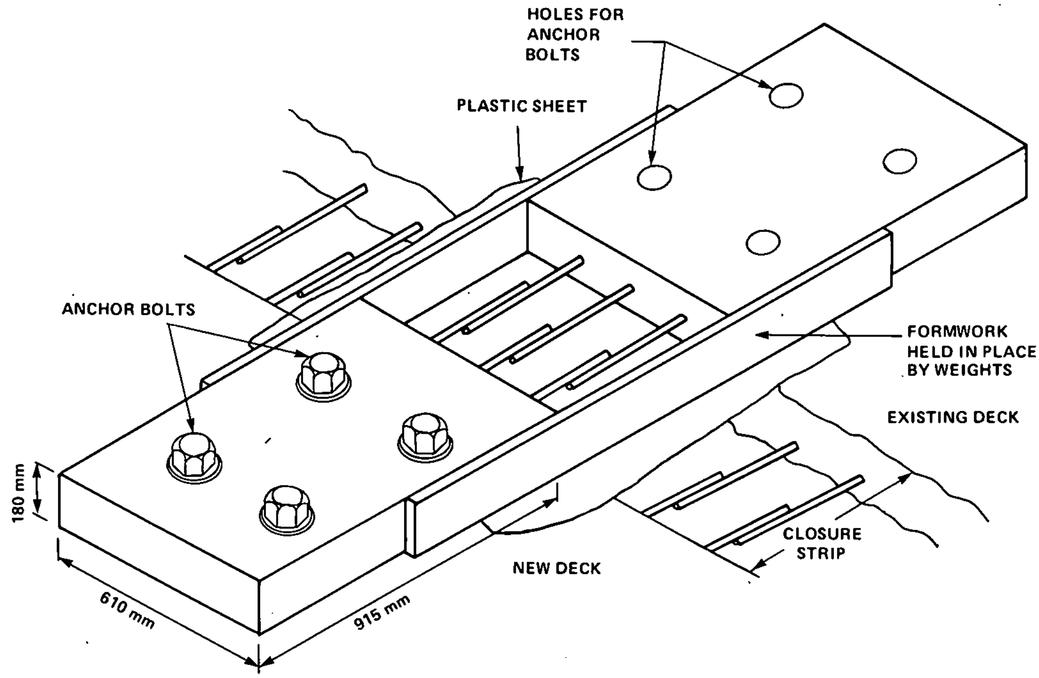


FIGURE 6 Arrangement of test blocks before casting closure strip.

embedded approximately 8 in. (200 mm) along its longitudinal axis. Pull-out tests were performed in accordance with methods given by Lutz (*91*), and the bond strength was calculated according to procedures given by Jiminez et al. (*92*).

The results of the test on one bridge were an average bond strength of 1470 psi (10.14 MPa) for the pieces cut from the control specimen and 1460 psi (10.07 MPa) for the pieces cut from the specimen simulating the closure pour. The scatter of the results of the six pieces was somewhat larger for the latter case. The results from the second test were an average bond strength of 1300 psi (9.0 MPa) for the control specimen and 1070 psi (7.4 MPa) for the specimen exposed to the effects of traffic. No evidence of voids around the steel or other defects indicating reduced bond strength were reported.

The tests reveal little, if any, detrimental effects from maintaining traffic during placement of a closure pour. These particular tests were made on structures where the closure pour was only 18-in. (460-mm) wide and the separation between the outside beams of the old deck and the inside beam of the widening was 3 ft (0.9 m). The investigation is continuing in order to determine if traffic-induced vibrations have an adverse effect in wider closure pours so that a comprehensive policy for the construction of widenings can be formulated.

## DECK REPLACEMENT

Deck replacement may be accomplished using either concrete cast in situ or precast slabs. Concrete cast in situ in a deck replacement using staged construction while traffic is maintained on the deck is subjected to the same conditions as concrete placed in bridge widenings. Consequently, the information contained in this chapter on bridge widenings is also applicable to deck replacement.

The only known investigation carried out to determine whether traffic-induced vibrations are detrimental to the bond between concrete and embedded reinforcement during deck slab replacement was undertaken by the Massachusetts Department of Public Works (*93*). The pull-out and compressive strengths of laboratory specimens were compared with the pull-out strength of bars in a replacement deck slab and with field cylinders subject to vibration, respectively. The field tests were conducted on an expressway viaduct in Boston where the deck slab was being replaced while traffic was maintained in adjacent lanes. It was reported that the traffic was causing large vibrations in exposed reinforcing bars. Three reinforcing bars at the quarter points of a 90-ft (27.4-m) span were cut such that the embedment of the new deck slab would be 18 in. (460 mm). A fourth bar was cut to an 18-in. (460-mm) embedment after placing the concrete. Cylinders were cast on site and allowed to remain on the span undergoing reconstruction for 24 hr before transfer to the laboratory curing room. The laboratory specimens were prepared from concrete having the same mixture proportions as the replacement deck slab. The four pull-out specimens consisted of a No. 6 (19-mm diameter) reinforcing bar embedded 18 in. (460 mm) in a 6- by 6- by 21-in. (150- by 150- by 530-mm) concrete specimen.

Pull-out tests were conducted on the laboratory specimens and on the four bars that had been cut from the deck slab at the age of 5 days. All the field tests failed by fracture of the reinforcement in tension at an average stress of 86,000 psi (590 MPa), corresponding to an average bond stress of 890 psi (6.1 MPa). The laboratory specimens also failed at an average stress of 86,000 psi (590 MPa); however, this was due to bond failure, which probably occurred as the result of the lack of confinement of the concrete in the laboratory specimens as compared to the concrete in the deck slab. The average compressive strength of the field cylinders on day 7 was 5750 psi (39.5 MPa) compared to 4400 psi (30.3 MPa) for the laboratory specimens. The cylinder results confirm the additional strength derived from continuous vibration of concrete during the setting period reported in Chapter 3. The pull-out tests demonstrate that the traffic vibrations had no effect on the bond strength of the reinforcement despite the fact that the annual average daily traffic for the structure was 3900 and the structure was selected because the amplitude of traffic-induced vibrations appeared to be large.

Precast slabs were used in the redecking of a large structure on the Pennsylvania Turnpike in 1979 and 1980 *(94, 95)*. The report describing the reason for the selection of precast slabs expresses many of the concerns about traffic-induced vibrations *(95)*: "Vibrations from the traffic can interfere with proper concrete setting. . . . If you pour on one side of a bridge and leave the other side open to traffic, you may have difficulties with the bond between the adjacent sections. In particular, the transverse rebars, which will protrude from the deck sections already cast and now bearing traffic, will vibrate while the contractor is pouring the adjacent section and trying to align the rebars."

Such beliefs are widely held, but no evidence is offered in support of the statements. The investigations on the performance of concrete in bridge widenings suggest that the concerns are unfounded. The principal benefits from the use of precast slabs for deck replacement accrue from speed of construction and not having to construct formwork under difficult site conditions rather than from avoiding the effects of traffic-induced vibrations.

## SUMMATION

Concrete in a bridge widening is more vulnerable to the effects of traffic-induced vibrations than concrete in an overlay, especially at the time of initial set. However, as with concrete overlays, the number of reports in the literature is small, although a few detailed investigations of the performance of overlays have been published.

Most agencies routinely permit traffic on a deck during full-depth repairs or widening of a deck and there are few documented cases of poor performance. This is largely explained by the fact that good-quality concrete has been shown to be unaffected by continuous vibration. Measurements have shown that the maximum curvature in a typical highway bridge is less than that which causes cracking in the concrete. The problems experienced in bridge widenings in Michigan in the mid- and late 1960's appear to have been caused by excess water in the concrete and shallow concrete cover over the reinforcement, which resulted in planes of weakness and premature failure of the deck slabs.

Extensive investigations of the performance of widenings in California and Texas have not indicated any adverse effects of traffic-induced vibrations except for one particular reinforcing detail.

Any benefits from the use of temporary shoring have not been proven.

CHAPTER SIX

# CONCLUSIONS AND RECOMMENDATIONS

## CONCLUSIONS

Despite the concerns and opinions of many design and construction personnel, there have been only two documented cases of adverse effects from traffic-induced vibrations on bridge-deck repairs, overlays, or widenings. One case was the rippling and fracture-plane development in bridges widened in Michigan in the mid- and late 1960's. It is now believed that the primary cause of the deficiencies was the use of excess water in the concrete and shallow concrete cover over the reinforcement, compounded by difficult construction conditions. The second case was the presence of voids around the reinforcing steel near the joint line in one bridge widening in Texas. The deficiency was attributed to an unusual reinforcement detail. Other investigations have shown that, *provided the concrete is well-proportioned,* traffic-induced vibrations do not cause:

- Segregation of the fresh concrete,
- Slow setting of the concrete,
- Poor bond to existing concrete,
- Bond failure to reinforcement,
- Poor strength development of the concrete,
- Differential consolidation, or
- Cracking in the fresh concrete.

The results of literature reviews, questionnaires, laboratory investigations, field experience, performance surveys, and on-site measurements lead to the following conclusions:

1. The policy of the vast majority of agencies is to maintain traffic on a structure during widening or application of a concrete overlay. In many cases, detour of traffic from a structure is not a practicable alternative.
2. The human body is sensitive to the presence of vibrations but unreliable in assessing the amplitude and frequency of vibrations.
3. Good-quality plain and reinforced concrete are not adversely affected by jarring and vibrations of low frequency and amplitude during the period of setting and early strength development.
4. Numerous surveys of the condition of concrete overlays have not shown any significant difference between the performance of overlays constructed on decks closed to traffic and those constructed while traffic was maintained.
5. Investigations of the condition of widened bridges have shown the performance of attached widenings, with and without the use of a closure pour, to be satisfactory.
6. The maximum transverse curvature in the fresh concrete in a typical bridge widening is less than the curvature necessary to cause cracking.
7. Studies have shown that traffic-induced vibrations do not cause relative movement between fresh concrete and embedded reinforcement.
8. Any benefit from temporary shoring has not been proved.

## RECOMMENDED PROCEDURES

The recommendations presented below have been formulated from the conclusion that there is insufficient evidence to show that traffic-induced vibrations have an adverse effect on high-quality concrete placed in bridge decks using good construction practice. This does not mean that the effects of traffic and traffic-induced vibrations can be ignored in constructing bridge-deck overlays and widenings. Often the safety of the road users and construction workers will dictate the traffic-control plan. Engineering judgment should be used to minimize traffic-induced vibrations where this can be done without greatly affecting the cost of the project or causing inconvenience to the road user. Such measures include use of an existing detour within the highway right of way, keeping trucks out of the adjacent lane during placing operations on the basis of voluntary compliance, or the release of diaphragms to reduce load transfer between an existing deck and a widening where a closure pour will be used.

The recommendations are applicable to most contracts for bridge repairs or reconstruction. The procedures are addressed specifically to the avoidance of problems arising from vibrations. The references cited in this report should be consulted for additional information on materials, proportions, and recommended construction practices. Where the type of structure or the proposed method of repair is unusual, or a serious safety problem exists, a full engineering analysis is required and these recommendations should be used only for guidance.

### Traffic Control

1. There is no documented evidence to require the detour of traffic from a structure during construction of a concrete overlay, concrete repair, barrier wall, or widening in order to avoid the effects of traffic-induced vibrations. Where decks are closed to traffic it should be for reasons of safety, to substantially reduce construction time, or where a suitable detour already exists. Substantial cost savings can be realized from the use of lane closures instead of temporary median crossovers on divided highways.
2. Because vibrations are primarily the result of vehicles passing over an irregularity in the bridge approach or deck surface, the most effective way to reduce the amplitude of traffic-induced vibrations is to maintain a smooth riding surface. Particular attention should be paid to patching potholes and maintaining a smooth transition at expansion joints and temporary ramps.

3. Speed and weight restrictions have only a secondary effect on the magnitude of traffic-induced vibrations. Therefore, limits should be established using safety as the main criterion.

4. A traffic-control plan should be prepared early in the planning stage of a contract for bridge repairs or reconstruction.

### Concrete Overlays

The highest standards of construction and inspection should be maintained. Particular attention should be paid to: (a) proportioning concrete with a maximum water-cement ratio of 0.40 and using a minimum water content consistent with placing conditions; (b) achieving the specified thickness of overlay and a smooth riding surface; and (c) applying the curing as soon as possible after placement of the concrete, because overlays are susceptible to plastic and drying shrinkage.

### Bridge Widenings and Slab Replacement

1. Widenings and new slabs should be attached to the existing structure. Moment transfer should be provided through the joint between the new and existing portions of the deck. Lapped reinforcing bars are preferable to dowels. The laps should be tied securely or welded. Dowels and reinforcing steel should be straight. A concrete keyway is not necessary.

2. A closure pour is recommended to achieve a smooth surface when an overlay will not be placed on the deck.

3. Where the fascia beam of the existing structure differs from the other beams in either section or camber, it should be removed and used as the fascia beam in the new deck.

## CURRENT RESEARCH

The following research projects are relevant to this study:

1. *Bridge Widening Study*—Georgia Department of Transportation Research Project No. 7604. This is a 2-yr investigation begun in 1979.

2. *Effects of Innovative Procedures on Concrete Bridge Decks*—University of Kansas under the sponsorship of Kansas Department of Transportation. This is a 2-yr study initiated in June 1980. One objective of the study is to "determine the effects of traffic-induced vibrations and deflections for bridge decks reconstructed under traffic on bleeding, cracking and steel-concrete bond strength considering full depth and partial depth repair, cover, deck thickness, bar size and spacing, and concrete slump and air content."

3. Several states are undertaking routine condition surveys of selected concrete overlays. These surveys will provide additional information on long-term performance.

## FUTURE RESEARCH NEEDS

This synthesis report differs from other reports in the series in that it was prepared specifically to determine whether a project statement should be prepared for research into problems arising from the effects of traffic-induced vibrations on fresh concrete in bridge decks. The study has concluded that there is no evidence that maintaining traffic on a structure undergoing repair or widening has an adverse effect on the future service life of the structure—provided that the recommendations given in this report are followed. Consequently, the recommendation of the study is not to fund additional research on this subject.

# REFERENCES


1. *Manual on Uniform Traffic Control Devices for Streets and Highways*. 1978. Federal Highway Administration, U.S. Department of Transportation.
2. Transportation Research Board. 1969. *NCHRP Synthesis of Highway Practice 1: Traffic Control for Freeway Maintenance*. Transportation Research Board, National Academy of Sciences, Washington, D.C.
3. Transportation Research Board. 1974. *NCHRP Synthesis of Highway Practice 25: Reconditioning High-Volume Freeways in Urban Areas*. Transportation Research Board, National Academy of Sciences, Washington, D.C.
4. MEYER, A.H., W.B. LEDBETTER, A.H. LAYMAN, and D. SAYLAK. 1978. *NCHRP Report 196: Reconditioning Heavy-Duty Freeways in Urban Areas*. Transportation Research Board, National Academy of Sciences, Washington, D.C.
5. MANNING, D.G., and R.P. NORTHWOOD. 1980. The rehabilitation of structures on an urban freeway—a case study. Pp. 644–668 in *Proceedings of the Bridge Maintenance and Rehabilitation Conference*. University of West Virginia.
6. Traffic safety in highway and street work zones; separation of opposing traffic. 1979. *Federal Register* 44 (181).
7. Traffic safety in highway and street work zones; separation of opposing traffic and edge of pavement excavation requirements. 1980. *Federal Register* 45 (202).
8. LISLE, F.N., and B. T. HARGROVES. 1979. Evaluation of the Performance of Portable Precast Concrete Traffic Barriers. Report No. VHTRC 80-RP10. Virginia Highway and Transportation Research Council.
9. WHIFFEN, A.C., and D.R. LEONARD. 1971. A Survey of Traffic-Induced Vibrations. Report LR418. Transport and Road Research Laboratory, England.
10. COLE, D.G. and D.C. SPOONER. 1968. The damping capacity of concrete. Pp. 217–224 in *Proceedings of an International Conference, London 1965*. Cement and Concrete Association, London.
11. JORDAN, R.W. 1980. The effect of stress, frequency, curing, mix and age upon the damping of concrete. *Magazine of Concrete Research* (London) 32 (113): 195–205.
12. FLEMING, J.F., and J.P. ROMUALDI. 1961. Dynamic response of highway bridges. *Journal of Structural Division, ASCE* 87 (ST7): 31–61.
13. LEONARD, D.R., J.W. GRAINGER, and R. EYRE. 1974. Loads and Vibrations Caused by Eight Commercial Vehicles with Gross Weights Exceeding 32 Tons (32.5 Mg). Report LR582. Transport and Road Research Laboratory, England.
14. PAGE, J. 1976. Dynamic Wheel Load Measurements on Motorway Bridges. Report LR722. Transport and Road Research Laboratory, England.
15. TROTT, J.J. 1966. An Analogue Computer Study to Determine the Influence of Vehicle Characteristics on the Dynamic Loading Produced by the Passage of a Vehicle over a Surface Irregularity. Technical Note No. 89. Transport and Road Research Laboratory, England.
16. CSAGOLY, P.F., T.I. CAMPBELL, and A.C. AGARWAL. 1972. Bridge Vibration Study. Report No. RR181. Ontario Ministry of Transportation and Communications.
17. CAMPBELL, T.I., P.F. CSAGOLY, and A.C. AGARWAL. 1979. Frequency matching in continuous post-tensioned concrete highway bridges. Pp. 139–154 in No. SP-60. American Concrete Institute, Detroit, Mich.
18. LEONARD, D.R. 1966. Human Tolerance Levels for Bridge Vibrations. Report LR34. Transport and Road Research Laboratory, England.
19. KOSTEM, C.N. 1978. Dynamic properties of skewed beam-slab highway bridges. Pp. 32–33 in *Transportation Research Record 676*. Transportation Research Board, National Academy of Sciences, Washington, D.C.
20. BILLING, J.R. 1979. Estimation of the Natural Frequencies of Continuous Multi-Span Bridges. Report No. RR219. Ontario Ministry of Transportation and Communications.
21. CUDNEY, G.R. 1965. Damping Bridge Vibration During Construction Widening. Research Report R-538. Michigan State Highway Department.
22. EDWARDS, A.T., and T.D. NORTHWOOD. 1960. Experimental studies of the effects of blasting on structures. *The Engineer* (London) 210: 538–546.
23. BROWN, L.M. 1971. Measurements of Vibrations Caused by Construction Equipment and Blasting. Report No. RR172. Ontario Ministry of Transportation and Communications.
24. NORTHWOOD, T.D., R. CRAWFORD, and A.T. EDWARDS. 1963. Blasting vibrations and building damage. *The Engineer* (London) 215: 973–978.
25. AKINS, K.P., and D.E. DIXON. 1979. Concrete Structures and Concrete Vibrations. Pp. 213–247 in No. SP-60. American Concrete Institute, Detroit, Mich.
26. WISS, J.F., and R.A. PARMALEE. 1974. Human Perception of Transient Vibrations. *Structural Engineering Journal, ASCE* 100 (ST4): 773–787.
27. WRIGHT, D.T., and R. GREEN. 1959. Human Sensitivity to Vibrations. Report No. 7. Department of Civil Engineering, Queen's University at Kingston, Ontario.
28. ORIARD, L.L. 1972. Blasting operations in the urban environment. *Bulletin of the Association of Engineering Geologists* IX (1): 27–46.
29. WISS, J.F. 1974. Vibrations during concrete operations. *Construction Engineering Journal, ASCE* 100 (CO3): 239–246.
30. Transportation Research Board. 1977. *NCHRP Synthesis of Highway Practice 44: Consolidation of Concrete for Pavements, Bridge Decks, and Overlays*. Transportation Research Board, National Academy of Sciences, Washington, D.C.

31. POPOVICS, S. 1972. Material aspects of concrete consolidated by vibration. *Materials and Structures*, RILEM 5 (27): 143–149.
32. POPOVICS, S. 1973. A review of concrete consolidation by vibration. *Materials and Structures*, RILEM 6 (36): 453–463.
33. AHMAD, K., and I.J. SMALLEY. 1974. Good vibrations. *Civil Engineering* (London) (July/August): 38–45.
34. KIRKHAM, R.H.H., and M.G. WHITE. 1962. The Compaction of Concrete Road Slabs. Technical Paper No. 54. Transport and Road Research Laboratory, England.
35. ACI Committee 309. 1981. Behavior of fresh concrete during vibration. Pp. 36–53 in *Proceedings, American Concrete Institute*. Vol. 78.
36. ACI Committee 309. 1971. Recommended practice for consolidation of concrete. Pp. 893–932 in *Proceedings, American Concrete Institute*. Vol. 68.
37. READING, T.J. 1967. What you should know about vibration. *Concrete Construction* 12: 213–217.
38. ACI Committee 212. 1971. Guide to the use of admixtures in concrete. Pp. 646–676 in *Proceedings, American Concrete Institute*. Vol. 68.
39. MATTISON, E.N. 1959. Some experiments with delayed and repeated vibration of concrete. *Constructional Review* 32 (9): 29–33.
40. TUTHILL, H.L., and H.E. DAVIS. 1938. Overvibration and revibration of concrete. Pp. 41–47 in *Proceedings, American Concrete Institute*. Vol. 35.
41. SAWYER, D.H., and S.F. LEE. 1956. The Effects of Revibration on Properties of Portland Cement Concrete. Pp. 1215–1227 in *Proceedings of ASTM*. Vol. 56. ASTM, Philadelphia.
42. VOLLICK, C.A. 1958. Effects of revibrating concrete. Pp. 729–732 in *Proceedings, American Concrete Institute*. Vol. 54.
43. HILSDORF, H.K., and J.L. LOTT. 1970. *NCHRP Report 106: Revibration of Retarded Concrete for Continuous Bridge Decks*. Transportation Research Board, National Academy of Sciences, Washington, D.C.
44. BASTIAN, C.E. 1970. The effect of vibration on freshly poured concrete. *Foundation Facts* 6 (1): 14–17.
45. FULLER, F.M. 1980. Discussion of the effect of coal mill vibration on fresh concrete. *Concrete International* 2 (10): 94–96.
46. AVRAM, C., N. VOINA, and O. MIRSU. 1967. The effect of revibration on the properties of cement paste and concrete. *Revue des Materiaux de Construction* 619: 141–153. [in French]
47. ABRAMS, D.A. 1919. Effect of vibration, jigging and pressure on fresh concrete. Pp. 63–85 in *Proceedings, American Concrete Institute*. Vol. 15.
48. ACI Committee 101. 1931. Current researches on plain and reinforced concrete and related materials. Pp. 469–510 in *Proceedings, American Concrete Institute*. Vol. 27.
49. Effect of Jarring on Fresh Concrete. 1948. P. 38 in No. St-13. Portland Cement Association, Skokie, Ill.
50. MEYER, E.V. 1955. Concrete exposed to vibration or shock during the entire setting period. *Betonteknik* (Stockholm) XI (4): 140–142. [in Swedish]
51. KRELL, W.C. 1979. The effect of coal mill vibration on fresh concrete. *Concrete International* 12: 31–34.
52. FURR, H.L., and L. INGRAM. 1972. Concrete overlays for bridge deck repair. Pp. 93–103 in *Highway Research Record 400*. Highway Research Board, National Academy of Sciences, Washington, D.C.
53. LARNACH, W.J. 1952. Changes in bond strength caused by re-vibration of concrete and the vibration of reinforcement. *Magazine of Concrete Research* (London) (No. 10): 17–21.
54. Transportation Research Board. 1979. *NCHRP Synthesis of Highway Practice 57: Durability of Concrete Bridge Decks*. Transportation Research Board, National Academy of Sciences, Washington, D.C.
55. ACI Committee 546. 1980. Guide for repair of concrete bridge superstructures. *Concrete International* 2 (9) 69–88.
56. Transportation Research Board. 1977. *NCHRP Synthesis of Highway Practice 45: Rapid-Setting Materials for Patching of Concrete*. Transportation Research Board, National Academy of Sciences, Washington, D.C.
57. Transportation Research Board. 1976. *NCHRP Research Results Digest 85: Bridge Deck Repairs*. Transportation Research Board, National Academy of Sciences, Washington, D.C.
58. CLEAR, K.C. 1976. Time-to-Corrosion of Reinforcing Steel in Concrete Slabs. Vol. 3. Performance after 830 Daily Salt Applications. Report No. FHWA-RD-76-70. Federal Highway Administration, U.S. Department of Transportation.
59. BROWN, L.M. 1974. Vibrations from Concrete-Breaking Operations. Report No. IR55. Ontario Ministry of Transportation and Communications.
60. BROWN, B.C. 1979. A Further Evaluation of Concrete Bridge Deck Surfacing in Iowa. Iowa Department of Transportation.
61. HAGEN, M.G., and R.G. TRACY. 1978. Bridge Deck Deterioration and Restoration Investigation No. 639. Interim Report III. Minnesota Department of Transportation.
62. BISHARA, A.G. 1979. Latex-Modified Concrete Bridge Deck Overlays—Field Performance Analysis. Report No. FHWA-OH-79-004. Ohio Department of Transportation.
63. OWENS, M.J., and D.G. MANNING. 1981. The Performance of Concrete Overlays on Bridge Decks (1976–1979). Report ME-80-02. Ontario Ministry of Transportation and Communications.
64. MANNING, D.G., and M.J. OWENS. 1979. Ontario's Experience with Concrete Overlays for Bridge Decks. *RTAC Forum* 2 (1): 31–37.
65. TRACY, R.G. Bridge Deck Deterioration and Restoration Investigation No. 639. Interim Report (Dec. 1976). Minnesota Department of Transportation.
66. SMUTZER, R.K., and R.B. HOCKETT. 1980. Investigation of Cracks in Latex-Modified Portland Cement Concrete Bridge Deck Overlays. Phase I: Field Investigations. Indiana State Highway Commission.
67. SMUTZER, R.K., and R.B. HOCKETT. 1980. Investigation

of Cracks in Latex-Modified Portland Cement Concrete Bridge Deck Overlays. Phase II: Concrete Laboratory Investigations. Indiana State Highway Commission.

68. BERGREN, J.V., and B.C. BROWN. 1975. An Evaluation of Concrete Bridge Deck Surfacing in Iowa. Special Report. Iowa Department of Transportation.
69. Bridge Deck Overlays with Latex-Modified Concrete, Experimental Construction Projects Category 2. Final Report. 1980. South Dakota Department of Transportation.
70. ACI Committee 224. 1980. Control of cracking in concrete structures. *Concrete International* 2 (10): 35–76.
71. KUHLMANN, L.A. 1981. Discussion of control of cracking in concrete structures. *Concrete International* 3 (5): 103.
72. MANNING, D.G. 1981. Discussion of control of cracking in concrete structures. *Concrete International* 3 (5): 103–104.
73. ACI Committee 224. 1981. Committee closure of control of cracking in concrete structures. *Concrete International* 3 (5): 107–110.
74. BUKOVATZ, J.E., C.F. CRUMPTON, and H.E. WORLEY. 1973. Bridge Deck Deterioration Study. Final Report. State Highway Commission of Kansas.
75. LAANINEN, K.H. 1978. Low Slump Portland Cement Concrete Bridge Deck Overlays. Research Report No. R-1077. Michigan State Highway Commission.
76. ARNOLD, C.J. 1980. Concrete Bridge Decks: Does Structural Vibration Plus Excess Water Form the Fracture Plane? Internal Report. Michigan Department of Transportation.
77. OEHLER, L.T., and G.R. CUDNEY. 1966. Deck Rippling on the I-175-Rouge River Bridge. Research Report No. R-607. Michigan Department of State Highways.
78. ARNOLD, C.J. 1966. Deck Rippling on Various Michigan Bridges—Third Progress Report. Research Report No. R-608. Michigan Department of State Highways.
79. CUDNEY, G.R. 1966. Fracture-Plane Deterioration of Concrete Bridge Decks. Research Report No. R-584. Michigan Department of State Highways.
80. AXON, E.O., D. E. GOTHAM, and R.W. COUCH. 1963. Investigative techniques used or contemplated. Pp. 3–11 in *Highway Research Board Bulletin 323*. Highway Research Board, National Academy of Sciences, Washington, D.C.
81. A Study of Deterioration in Concrete Bridge Decks. 1965. Report on Investigation 59-2A. Missouri State Highway Department.
82. AXON, E.O., L.T. MURRAY and R.M. RUCKER. 1969. A study of deterioration in concrete bridge decks. Pp. 80–88 in *Highway Research Record 268*. Highway Research Board, National Academy of Sciences, Washington, D.C.
83. ARNOLD, C.J., M.A. CHIUNTI, and K.S. BANCROFT. 1976. A Review of Bridge Deck Problems and a Final Report on the Performance of Several Berrien County Structures That Were Widened Under Traffic. Research Report No. R-1008. Michigan State Highway Commission.
84. ARNOLD, C.J. 1976. Bridge Decks in Michigan: A Summary of Research and Performance. Michigan State Highway Commission.
85. ARNOLD, C.J., M.A. CHIUNTI, and K.S. BANCROFT. 1975. Experimental Shoring to Reduce Vibration During Bridge Deck Widening—Progress Report: 9 Year Performance. Research Report No. R-951. Michigan State Highway Commission.
86. MCMAHAN, J.E., and J.C. WOMAC. 1965. Bridge Widening Problems. Report No. 951120 HPR-1(2), DO 422. California Division of Highways.
87. SHAW, T.V., and C.F. STEWART. 1974. Effectiveness of Bridge Widenings. Report No. CA-DOTDS-4165-1-74-2. California Division of Highways.
88. Widening Existing Bridges. California Department of Transportation Memo to Designers 9-3, March 1979.
89. Deep Girders on New Piers Widen Busy Turnpike. *Engineering News-Record,* June 27, 1974. pp. 14–15.
90. FURR, H.L., and F.H. FOUAD. 1981. Bridge Slab Concrete Placed Adjacent to Moving Live Loads. Report No. FHWA/TX-81/11+266-1F. Texas Department of Highways and Public Transportation.
91. LUTZ, L.A. 1970. Information on the bond of deformed bars from special pullout tests. Pp. 885–887 in *Proceedings, American Concrete Institute*. Vol. 67.
92. JIMINEZ, R., R.N. WHITE, and P. GERGELY. 1979. Bond and dowel capacities of reinforced concrete. Pp. 73–78 in *Proceedings, American Concrete Institute* Vol. 76.
93. Pull-Out Test on Steel Reinforcing Bars Subject to Vibration. (Circa 1974.) Massachusetts Department of Public Works.
94. Precasting Speeds Bridge Re-decking. 1979. *Engineering News-Record,* August 16, p. 15.
95. KNUDSEN, C.V. 1980. Re-decking a bridge with precast concrete. *Civil Engineering, ASCE* (April): 75–77.
96. TRACY, R.G. 1979. Priority assignment for bridge deck repairs. Pp. 50–55 in *Transportation Research Record 727*. Transportation Research Board, National Academy of Sciences, Washington, D.C.

# APPENDIX A

## SURVEY OF CURRENT PRACTICE

To determine the practices of agencies in handling traffic during bridge repairs and widenings, a survey form (Figure A-1) was mailed to all states in March 1980. Forty-five states and the District of Columbia responded to the survey (Table A-1). Following is a summary of the responses and comments for each question on the survey form.

*Question 1.* All states permit traffic to continue using one or more lanes of a bridge, with one exception (Hawaii) when undertaking partial-depth repairs and with two exceptions (Hawaii and South Dakota) when undertaking full-depth repairs or widenings. Where a suitable detour exists, most agencies will close a bridge to traffic while repairs are being made, but this is done infrequently.

*Question 2.* The responses indicated that traffic restrictions are imposed in many states. However, traffic speed is normally reduced by the imposition of a construction safety zone and is often reduced further by lane-control devices or congestion at the construction site. Four states either prohibit trucks or limit vehicle weight at some sites; two states impose lane restrictions on trucks, and six states impose lane restrictions that were not specified in their responses. In general, the same restrictions apply to partial- and full-depth repairs. One state reported that concrete placement may be required to coincide with minimum traffic volumes. Two states sometimes require placement at night, although this requirement is dictated by weather conditions rather than by traffic considerations.

*Questions 3 and 4.* There appears to be a great deal of uniformity among the repair methods used by various agencies. This means that most precautions for deck preparation and concrete placement are contained in well-established specifications. Some states do take extra precautions in widenings: two states cited the use of shoring to control live-load deflections, and three states isolate the widening from the remainder of the deck and complete the work with a closure pour.

*Question 5.* The policies of some states are based on the fact that there is simply no alternative to permitting traffic on the deck; i.e., no detour exists at most sites. It should also be noted that a detour may have a negative impact on safety. The majority of states base their policy on engineering judgment that, in the absence of evidence to the contrary, the practice has no adverse effects on the restored deck or, if adverse effects result, these are outweighed by the cost of diverting traffic. Five states reported that their policy was based on the results of systematic surveys, indicating that traffic on the deck does not produce any significant adverse effects. However, supporting documentation was not offered; therefore, follow-up letters were sent to these five respondents. Where additional information was provided, this was included in the body of the synthesis.

*Question 6.* In all cases where traffic is prohibited from adjacent lanes, this practice is based on engineering judgment that traffic, especially trucks, may have an adverse effect on the restored deck.

*Question 7.* The responses to this question must be interpreted carefully. Many states reported no defects in repaired bridge decks; however, there is an obvious reluctance to disclose defects. The questionnaire did not attempt to determine frequency of occurrence of defects. Consequently, where defects are reported in the tabulated responses, the defects may have occurred frequently on restored bridges in the state, or they may be limited to a single structure. Nor did the questionnaire attempt to ascertain the severity of the defects. No distinction was drawn between hairline cracks and wide cracks or between an isolated, small delamination and widespread delamination on a deck. The questionnaire did ask respondents to indicate deficiencies in three different types of concrete overlay. The differences among the three systems do not appear to be significant. Also, because the deficiencies were not expressed in a form proportional to the number of overlays of each type in a state, a direct comparison among the systems was not possible. The results have been tabulated as a composite of the responses. In addition to cracks, delamination, and debonding, two states reported an undulating riding surface as a deficiency in concrete overlays.

*Question 8.* Nine agencies indicated a belief that some of the defects that occurred in deck repairs resulted from traffic-induced vibrations during restoration. No data were offered in support of these statements. Follow-up letters were sent to these respondents; however, no further documentation was offered in support of these statements.

*Question 9.* Only two agencies (Texas and Georgia) have conducted research projects or field studies on the effect of traffic-induced vibrations on deck repairs. Neither of these studies was complete at the time of the survey.

State ____________________

SURVEY OF CURRENT PRACTICE AND ATTITUDES
ON MAINTAINING TRAFFIC DURING BRIDGE DECK RESTORATION OR WIDENING

1. Does your agency permit traffic to continue using one or more lanes of a bridge when concrete is being placed on the same structure?

   a) partial depth
      Yes _____ (go to questions 2-5)
      No _____ (go to question 6)

   b) full depth
      Yes _____ (go to questions 2-5)
      No _____ (go to question 6)

2. Do you impose any restrictions on the traffic (e.g. limit on speed or truck weight) or the concreting operation (e.g. time of day)?

   a) partial depth
      Yes _____ No _____
      If yes, please specify ____________________

   b) full depth
      Yes _____ No _____
      If yes, please specify ____________________

3. Do you take any special precautions with the new concrete itself?

   a) partial depth
      Yes _____ No _____
      If yes, please specify ____________________

   b) full depth
      Yes _____ No _____
      If yes, please specify ____________________

4. Do you take any special precautions with the existing deck?

   a) partial depth
      Yes _____ No _____
      If yes, please specify ____________________

   b) full depth
      Yes _____ No _____
      If yes, please specify ____________________

5. What is the basis for your agency's policy of permitting traffic to continue?

   _____ Your engineering judgment, in the absence of evidence to the contrary, that the practice would have no adverse effects on the restored deck?

   _____ Your judgment that while adverse effects may result, they are outweighed by the cost of diverting traffic?

   _____ Evidence from systematic surveys of restored decks indicating that traffic on the structure produces no significant adverse effects, when weighed against the cost of diverting traffic?

   _____ Experience and practice developed by other agencies or states?

   _____ Other, please specify. ____________________
   (go to question 7)

(OVER)

FIGURE A-1 Survey form mailed to all states in March 1980.

FIGURE A-1 *continued*

6. What is the basis of your agency's policy of prohibiting traffic in adjacent lanes?

   ____ Your engineering judgment that the practice would have significant adverse effects on the restored deck?

   ____ Evidence from systematic surveys of restored decks that the practice does have significant adverse effects on restored decks?

   ____ Experience and practice developed by other agencies or states?

   ____ Other, please specify.________________________________________

7. Have you prematurely experienced a significant incidence of any of the following defects in bridge deck concrete that had been subjected to traffic vibrations during restoration or widening? Indicate by checking (✓) the appropriate boxes.

| Defect | On Latex Modified Concrete/Mortar Overlay | On Low-void (Iowa) Overlay | On Conventional Concrete Overlay | On Full Depth Concrete | Other |
|---|---|---|---|---|---|
| Longitudinal cracks | | | | | |
| Transverse cracks | | | | | |
| Random cracks | | | | | |
| Failure of concrete bond | | | | | |
| Delamination at rebar level | | | | | |
| Inadequate concrete strength or durability | | | | | |
| Other, specify | | | | | |

8. Identify, by placing an asterisk (*) in the appropriate box, those defects listed in question 7 that you believe to be associated with or caused by traffic-induced vibrations during placement.

9. Has your agency conducted research projects or field studies on the effect of traffic induced vibrations upon concrete placed in bridge decks?

   Yes____ No____

   If yes, the individual to contact regarding this work is:

   Name________________________________ Phone____________________

10. Do you have bridge deck restoration or widening projects scheduled for the 1980 construction season?

    Yes____ No____

    If yes, the individual to contact regarding this work is:

    Name________________________________ Phone____________________

Name of respondent ________________________

Title________________________________ Phone____________________

TABLE A-1
RESPONSES TO QUESTIONNAIRE

| Agency | Traffic Permitted? Partial Depth | Full Depth | Restrictions and Precautions: Partial-Depth Repairs | Full-Depth Repairs and Widenings | Defects Observed: Partial-Depth Repairs | Full-Depth Repairs and Widenings |
|---|---|---|---|---|---|---|
| Alaska | Yes | Yes | Reduce speed | Reduce speed | Random cracks | |
| Arizona | Yes | Yes | Lane restrictions | Lane restrictions; shoring to control deflection | | |
| California | | Yes | | Widening isolated and closure pour used | | Fracturing of concrete adjacent to waterstops in widenings |
| Colorado | Yes | Yes | Reduce speed and lane restrictions | Shoring to control deflection | Transverse cracks | Transverse and random cracks |
| Connecticut | Yes | Yes | | Minimize setting time | Longitudinal cracks at ends of spliced bars | |
| Delaware | Yes | Yes | Max. 25 mph and 5-ton limit | Max. 25 mph and 5-ton limit | | Longitudinal cracks |
| Dist. of Col. | Yes | Yes | | | | Transverse cracks |
| Florida | Yes | Yes | | | | |
| Georgia | | Yes | | Widening isolated and closure pour used | | |
| Hawaii | No | No | | | | |
| Idaho | Yes | Yes | | Some widenings and staged redecking isolated from traffic | | |
| Illinois | Yes | Yes | Reduce speed | Reduced speed; sometimes loosen diaphragms | | |
| Indiana | Yes | Yes | | | | |
| Iowa | Yes | Yes | | | | |
| Kansas | Yes | Yes | Reduce speed | | Longitudinal and transverse cracks and delamination on older decks | |
| Kentucky | Yes | Yes | Sometimes prohibit trucks until concrete sets; occasionally use high-early-strength concrete | As for partial-depth repairs | Cracks, bond failure, and delamination | Bond failure and delamination at level of reinforcing steel |
| Maine | Yes | Yes | | | Transverse, longitudinal, and random cracks | |
| Maryland | Yes | Yes | Trucks prohibited in adjacent lane | Trucks prohibited in adjacent lane | | Slumping of concrete on superelevated decks |
| Massachusetts | Yes | Yes | Reduce speed; sometimes use quick-set materials | Reduce speed | | |
| Michigan | Yes | Yes | Max. 45 mph | Max. 45 mph | Random cracks and bond failure | |
| Minnesota | Yes | Yes | Varies - not specified | Varies - not specified | Transverse cracks, inadequate durability, and undulating surface | Transverse cracks, bond failure and delamination, inadequate durability, and undulating surface |
| Mississippi | | Yes | | | | |

TABLE A-1 *continued*

| Agency | Traffic Permitted? Partial Depth | Full Depth | Restrictions and Precautions Partial-Depth Repairs | Full-Depth Repairs and Widenings | Defects Observed Partial-Depth Repairs | Full-Depth Repairs and Widenings |
|---|---|---|---|---|---|---|
| Missouri | Yes | Yes | Sometimes schedule placement to coincide with minimum traffic volumes | As for partial-depth repairs | Cracks and bond failure | |
| Montana | Yes | Yes | Max. 35 mph | Max. 5 mph for 24 hr | | |
| Nebraska | Yes | Yes | Reduce speed | Reduce speed | | |
| Nevada | Yes | Yes | Not specified | Not specified | | |
| New Hampshire | Yes | Yes | Reduce speed; lane restriction for trucks | Reduce speed; lane restrictions for trucks | | |
| New Jersey | Yes | Yes | Lane restrictions | Lane restrictions | Random cracks and bond failure | Random cracks and bond failure |
| New Mexico | Yes | Yes | Reduce speed; sometimes use high-early-strength concrete | Reduce speed; sometimes use high-early-strength concrete | | |
| New York | Yes | Yes | Sometimes reduce speed, limit vehicle weight, and require concrete placement at night | As for partial-depth repairs | Cracks | Cracks |
| North Carolina | Yes | Yes | | | | |
| North Dakota | Yes | Yes | Reduce speed | Reduce speed and lane restrictions | | |
| Ohio | Yes | Yes | Reduce speed; sometimes require concrete placement at night | Reduce speed | Cracks, bond failure, and undulating surface | Transverse cracks |
| Oklahoma | Yes | Yes | Max. 30 mph | Max. 30 mph | Transverse and random cracks | Transverse and random cracks |
| Oregon | Yes | Yes | Lane restrictions | Lane restrictions | | |
| Pennsylvania | Yes | Yes | Reduce speed and limit vehicle weight | Lane restrictions; reduce speed and limit vehicle weight | Random cracks | Transverse cracks |
| Rhode Island | Yes | Yes | | | | |
| South Carolina | Yes | Yes | Sometimes reduce speed | Sometimes reduce speed | | |
| South Dakota | Yes | No | Max. 10 mph | | Transverse and random cracks | |
| Tennessee | Yes | Yes | | | Cracks, bond failure, and inadequate durability | Transverse cracks |
| Texas | Yes | Yes | | Sometimes lane restrictions | | |
| Utah | Yes | Yes | | | Random cracks, bond failure, and delamination | |
| Virginia | Yes | Yes | Reduce speed | Reduce speed | | |
| West Virginia | Yes | Yes | Reduce speed | Reduce speed | | |
| Wisconsin | Yes | Yes | Reduce speed; sometimes limit vehicle weight | Reduce speed; sometimes limit vehicle weight | Longitudinal, transverse, and random cracks | |
| Wyoming | Yes | Yes | Reduce speed | Reduce speed | | |

# APPENDIX B

## FIELD INSPECTIONS

During the course of the study, inspections were made of structures in Minnesota, New York, and Ontario. All the structures had either been widened or overlaid with concrete. Both bridges that had been repaired under traffic and those that had been repaired while traffic was detoured were inspected. Where possible, structures were selected to minimize differences in performance resulting from the type of structure, the nature of the repair, different contractors and construction procedures, age of the repair, and traffic volumes. The scope of the inspections was limited to a visual appraisal of the condition of the deck surface and a subjective assessment of the quality of ride on the structure.

### MINNESOTA

The results of the inspections, carried out in October 1980, are presented in Table B-1.

All of the structures included in the survey had been overlaid with low slump concrete in the period 1976–1979. A new deck slab had been constructed on three structures and one structure had been widened before placement of the overlay. It is the policy in Minnesota to give greatest priority to the rehabilitation of deteriorated decks in high and medium traffic volume locations and medium priority to the protection of good decks in high and medium traffic volume locations (96). Consequently, most of the structures inspected were on the Interstate highway system. Where the overlays were placed within 3 yr of construction of the bridge, the decks were generally in good condition and the overlay was placed as a protective treatment against future corrosion-induced spalling of the deck. Decks that were older at the time of overlay placement were badly deteriorated at the time of rehabilitation.

In general, all the overlays were in good condition. It was not possible to ascribe any differences in quality of ride or performance of the overlays to the presence or absence of traffic on the deck at the time of repair. There is, however, evidence that the degree of cracking in overlays depends on traffic loads on the structure after repair.

The transverse cracks adjacent to the south expansion joint in Structure No. 69846 are present only in the northbound lane and are thought to be caused by the impact loading of traffic, which is excited by irregularities in the approach pavement to the structure. Structure Nos. 69831/2 are 12-span parallel structures on I-35 in Duluth. Structure No. 69832 carries fully loaded grain trucks; the trucks return empty over Structure No. 69831. At the time of overlay in 1976, Structure No. 69832 was badly spalled and patches placed to restore the riding surface were short-lived. There was less deterioration on Structure No. 69831. Considerable vibration on the structures was reported at the time of overlay and some transverse cracking was observed after the first overlay placement. At the time of inspection in 1980, there were numerous transverse cracks in Structure No. 69832, especially in the center spans, but no defects were visible in Structure No. 69831. The difference in performance of the two structures appears to be related to the much heavier truck loading on Structure No. 69832.

Structure No. 5190 is an 11-span structure constructed in 1932 on Highway 2 over the St. Louis River. The deck slab was replaced and overlaid in 1977 while traffic was maintained on the structure. Construction conditions were difficult because of high traffic volumes and a narrow pavement. No cracking was reported after construction. Wide transverse cracks are now visible in the center truss spans. The cracks predominate in the eastbound lane, which is the lane used by trucks transporting grain to Duluth and Superior.

Structure Nos. 27906 and 27907 are of particular interest. These two structures have continuous steel beams and are located in an interchange between two freeways. The structures have a lively dynamic response. They were maintained open to traffic during placement of a low-slump overlay. Numerous wide transverse cracks with efflorescence are visible on the underside of the deck slab of Structure 27906 (see Figure B-1). These cracks were present at the time the overlay was placed but are not visible on the deck surface. The combination of structural type, heavy traffic loadings, and preexisting cracks in the deck slab are conditions that would be expected to accentuate any effects of traffic-induced vibrations on the concrete at the time of placement; yet no defects have been noted in the overlays in the first 2 yr of service.

### NEW YORK

The results of the inspection of 40 bridge decks, carried out in October 1980, are presented in Table B-2. Nineteen of the structures had been repaired while traffic was maintained on the structure and 21 were repaired while traffic was detoured from the structure.

All the structures included in the survey were on the Interstate network; four carried secondary highways over an Interstate highway, four were located on an exit ramp, and the remainder were located directly on the Interstate highway. The structures were selected to minimize the number of variables, other than traffic-induced vibrations at the time of repair, that could be expected to influence the performance of overlays. All the structures were built in the period 1963–1971 and rehabilitated through the application of a low-slump overlay in the period 1978–1980. The work was done only by three contractors. With two exceptions, all the structures consisted of a thin slab deck on simply supported steel

TABLE B-1
FIELD OBSERVATIONS IN MINNESOTA

| Bridge No. | Year Built | Type of Structure | Year of Repair | Repaired Under Traffic | Type of Repair | Quality of Ride | Condition of Deck |
|---|---|---|---|---|---|---|---|
| 9800 | 1968 | 29 span continuous deck girder | 1975 | Yes | Low-slump overlay | Fair | Few narrow transverse cracks |
| 70001 | 1965 | 3 span continuous steel beams | 1979 | Yes | Low-slump overlay | Good | No defects |
| 27079/80 | 1968 | 3 span continuous steel beams | 1979 | | Low-slump overlay | Good | No defects |
| 27973/4 | 1965 | 3 span continuous steel beams | 1978 | No | Low-slump overlay | Good | Light scaling near curbs |
| 27975/6 | 1965 | 3 span continuous steel beams | 1978 | No | Low-slump overlay | Good | Light scaling near curbs |
| 27977/8 | 1965 | 3 span continuous deck slab on simply supported prestressed concrete beams | 1978 | No | Low-slump overlay | Good | Light scaling in S.B. lanes. Single narrow transverse crack in W.B. lanes |
| 27907 | 1964 | 3 span continuous steel beams | 1977 | Yes | Low-slump overlay | Good | No defects |
| 27906 | 1964 | 3 span continuous steel beams | 1977 | Yes | Low-slump overlay | Good | No defects in overlay. Numerous medium transverse cracks in deck slab not reflected through overlay |
| 27917/8 | 1964 | 3 span continuous deck slab prestressed concrete beams | 1979 | Yes | Deck slab widened by 8 ft; low-slump overlay placed on entire deck | Good | No defects |
| 9792 | 1959 | 4 span continuous steel beams | 1978 | No | Low-slump overlay | Poor | No defects |
| 58807/8 | 1964 | 4 span continuous steel beams | 1979 | No | Bridges widened; new deck slab with low-slump overlay | Good | Several short, narrow cracks extending into overlay from contraction joints in barrier walls |
| 58811/2 | 1965 | 3 span continuous deck slab on simply supported prestressed beams | 1979 | Yes | Low-slump overlay | Good | No defects |
| 9815/6 | 1968 | 3 span continuous steel beams | 1979 | Yes | Low-slump overlay | Good | Few hairline transverse cracks in 9815 |
| 69846 | 1966 | 4 span continuous steel beams | 1978 | Yes | Low-slump overlay | Good | Few medium transverse cracks in N.B. lane adjacent to S. expansion joint |
| 69831/2 | 1967 | 12 span continuous steel beams | 1976 | Yes | Low-slump overlay | Good | No defects in 69831. Several medium transverse cracks in 69832, especially in center spans |
| 5190 | 1932 | 8 span, simply supported steel beams - 3 spans of deck trusses | 1977 | Yes | New deck slab with low-slump concrete overlay | Poor | Few wide transverse cracks in truss spans, especially in E.B. lane |

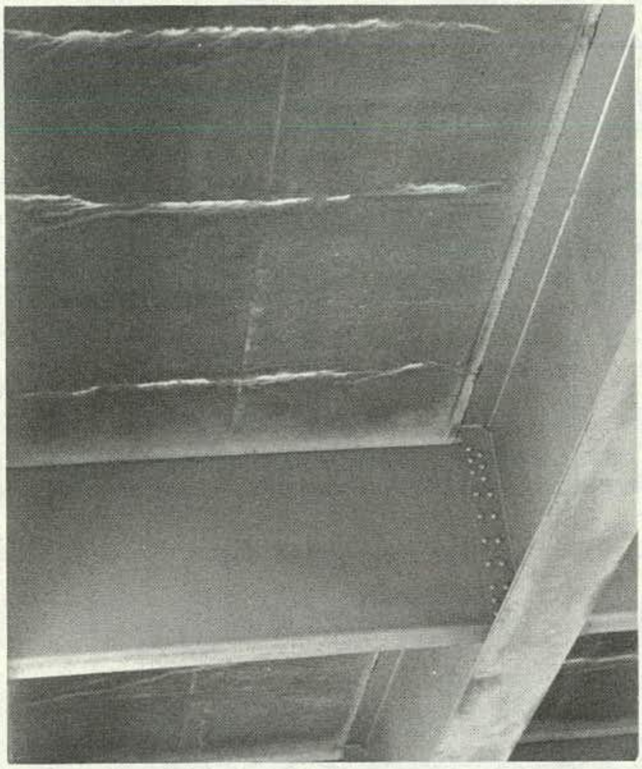

FIGURE B-1 Underside of deck slab of Structure 27906. The concrete overlay on the deck surface is free from cracks.

beams. Overlays of relatively new construction were chosen for inspection because any negative effects of traffic-induced vibrations, especially increased cracking or poor riding characteristics, would be expected to be visible soon after the decks were placed in service. After many years in service, these effects may be obscured by other factors that affect the service environment, such as the volume and type of traffic.

Few defects were observed and none that could be related to the presence of traffic on the deck at the time of repair. Only six of the decks had significant cracks in the overlay; these six decks had been repaired with no traffic on the deck. In four of the six bridges, the cracks were structural in origin, extending through the deck slab and resulting from details of a drainage grating in two cases and the skew of the deck in the other two. On the remaining two structures, the cracks in the overlay were hairline in width and more typical of the cracks observed by other agencies.

The riding quality of nine decks was assessed to be poor or fair; of these decks, five were open to traffic at the time of repair and four were closed. Grinding was necessary on four decks to improve the quality of the ride. Two of the four decks were open and two were closed to traffic when the overlays were placed. Consequently, there was no evidence that the riding quality of an overlay is affected by the presence of traffic-induced vibrations at the time of placement. Good results were noted on approximately 75 percent of the overlays inspected, of which half had been repaired under traffic and half had been repaired in the absence of traffic.

TABLE B-2
FIELD OBSERVATIONS IN NEW YORK

| Bridge No. | Year Built | Type of Structure | Year Repaired | Repaired Under Traffic | Type of Repair | Quality of Ride | Condition of Deck |
|---|---|---|---|---|---|---|---|
| 1008431/2 | 1966 | 3 span hinged steel beams | 1980 | No | Low-slump overlay | Good | No defects |
| 1031411/2 | 1966 | 3 span simply supported steel beams | 1980 | No | Low-slump overlay | Good | Median width diagonal cracks approx. 6-ft long in each span; small spall at one intermediate joint in S.B. structure |
| 1051149 | 1968 | 1 span simply supported steel beams | 1981 | No | Low-slump overlay | Fair | No defects; areas of grinding in W.B.L. |
| 1051159 | 1968 | 1 span simply supported steel beams | 1981 | No | Low-slump overlay | Good | No defects |
| 1051160 | 1968 | 4 span simply supported steel beams | 1981 | Yes | Low-slump overlay | Good | No defects |
| 1051081/2 | 1971 | 3 span simply supported steel beams | 1981 | No | Low-slump overlay | Good | No defects |
| 1064679 | 1971 | 3 span simply supported steel beams | 1981 | No | Low-slump overlay | Good N.B.<br>Fair S.B. | No defects |
| 1064689 | 1971 | 4 span simply supported steel beams | 1981 | No | Low-slump overlay | Poor N.B.<br>Fair S.B. | Areas of grinding in N.B.L. |

TABLE B-2 *continued*

| Bridge No. | Year Built | Type of Structure | Year Repaired | Repaired Under Traffic | Type of Repair | Quality of Ride | Condition of Deck |
|---|---|---|---|---|---|---|---|
| 1064691/2 | 1971 | 2 span simply supported steel beams | 1981 | No | Low-slump overlay | Good | Few longitudinal hairline cracks W.B.; numerous random hairline cracks E.B. |
| 1051120 | 1971 | 1 span simply supported steel beams | 1981 | Yes | Low-slump overlay | Fair | No defects |
| 1064650 | 1971 | 2 span simply supported steel beams | 1981 | Yes | Low-slump overlay | Good | No defects |
| 3064660 | 1970 | 1 span simply supported steel | 1981 | No | Low-slump overlay | Good | No defects |
| 1024911/2 | 1966 | 3 span simply supported steel beams | 1980 | Yes | Low-slump overlay | Fair | No defects; areas of grinding in N.B.L. |
| 1031351/2 | 1966 | 4 span simply supported steel beams | 1980 | Yes | Low-slump overlay | Poor S.B.<br>Fair N.B. | No defects; areas of grinding in S.B.L. |
| 1031341/2 | 1966 | 3 span simply supported steel beams | 1980 | Yes | Low-slump overlay | Good | No defects |
| 1031332 | 1966 | 3 span steel spandrel arch | 1980 | No | Low-slump overlay | Not open to traffic | No defects |
| 1031321/2 | 1966 | 3 span simply supported steel beams | 1980 | Yes | Low-slump overlay | Good | No defects; only one lane in each direction completed |
| 1031301/2 | 1966 | 3 span simply supported steel beams | 1980 | Yes | Low-slump overlay | Good | No defects; only one lane in each direction completed |
| 1031360 | 1966 | 6 span simply supported steel beams | 1980 | Yes | Low-slump overlay | Good | Few hairline longitudinal cracks at south expansion joist |
| 1031371/2 | 1966 | 5 span simply supported steel beams | 1980 | No | Low-slump overlay | Good | Medium width diagonal cracks originating from each drainage grating |
| 1031381/2 | 1966 | 3 span simply supported steel beams | 1980 | No | Low-slump overlay | Good | No defects |
| 1010431/2 | 1966 | 3 span simply supported steel beams | 1980 | No | Low-slump overlay | Good | Small spall at one joint |
| 1031390 | 1966 | 6 span simply supported steel beams | 1980 | Yes | Low-slump overlay | Good | No defects |
| 1064810 | 1966 | 3 span simply supported steel beams | 1980 | Yes | Low-slump overlay | Good | No defects |
| 1008400 | 1966 | 3 span simply supported steel beams | 1980 | Yes | Low-slump overlay | Good | No defects |
| 1064820 | 1966 | 3 span simply supported steel beams | 1980 | Yes | Low-slump overlay | Good | No defects |
| 1002131<br>1002132 | 1971<br>1963 | 3 span simply supported steel beams | 1981 | No | Low-slump overlay | Fair | No defects |

**ONTARIO**

The results of the inspection of 13 structures in Ontario, carried out in 1979, are given in Table B-3. Several types of structure were represented in the original survey (*63*). However, post-tensioned structures have not been included in the results given in Table B-3 because of complications arising from the susceptibility to reflective cracking of overlays placed on thick-slab, voided post-tensioned structures (*64*). The survey included checking the decks for delamination in addition to recording the presence of cracks. Where the data were available in a quantitative form, they are given in Table B-4. This table includes data on several of the structures reported in Table B-3, and also includes the results of the condition surveys made in 1980.

As in the case of the inspections in Minnesota and New

TABLE B-3
FIELD OBSERVATIONS IN ONTARIO

| Bridge No. | Year Built | Type of Structure | Year of Overlay | Traffic Maintained? | Type of Overlay | Quality of Ride | Condition of Deck |
|---|---|---|---|---|---|---|---|
| 798 | 1969 | 3 span reinforced concrete slab | 1978 | Yes | Latex-modified concrete | Fair | Fine transverse cracks at 18-in. (450-mm) intervals full length of deck; one small area of delamination |
| 6231 | 1968 | 4 span semi-continuous prestressed concrete beams | 1976 | Yes | Latex-modified concrete | Good | Hairline checkerboard cracks over entire deck surface; one small area of delamination |
| 6232 | 1968 | 4 span semi-continuous prestressed concrete beams | 1976 | Yes | Low-slump concrete | Fair | Several fine and medium cracks especially in N.B. lane adjacent to S. expansion joint; areas of delamination over N. pier and in N. span |
| 6233 | 1968 | 4 span semi-continuous prestressed concrete beams | 1978 | No | Latex-modified concrete | Fair | Hairline checkerboard cracks over entire deck surface |
| 14377 | 1976 | 3 span semi-continuous prestressed concrete beams | 1976 | No | Low-slump concrete | Good | Hairline transverse cracks over supports |
| 29196 | 1977 | 3 span continuous steel plate girders | 1977 | No | Low-slump concrete | Good | Medium width transverse cracks adjacent to piers |
| 30128 | 1967 | Single span steel beams | 1978 | Yes | Latex-modified concrete | Fair | Hairline transverse cracks at N. end of deck |
| 35404 | 1974 | 4 span semi-continuous prestressed concrete beams | 1977 | No | Latex-modified concrete | Good | Fine to medium checkerboard cracks over entire deck surface; small areas of delamination |
| 37167 | 1968 | 3 span semi-continuous prestressed concrete beams | 1976 | Yes | Low-slump concrete | Fair | Random cracks, medium in width, in E.B. lane adjacent to W. expansion joint; hairline transverse cracks over piers |
| 37343 | 1965 | Single span prestressed concrete beams | 1978 | Yes | Latex-modified concrete | Fair | No defects |
| 37784 | 1967 | 3 span semi-continuous prestressed concrete beams | 1978 | Yes | Latex-modified concrete | Good | No defects |
| 46228 | 1969 | 3 span continuous steel beams | 1977 | Yes | Low-slump concrete | Good | Hairline transverse cracks over piers |
| 47002 | 1969 | 3 span semi-continuous prestressed concrete beams | 1977 | Yes | Low-slump concrete | Good | Hairline transverse cracks over piers |

York, no defects were observed that could be attributed to traffic on the deck at the time of construction.

Three of the structures (Bridge Nos. 6231, 6232, and 6233) are of particular interest. The structures are identical in type and located within a few miles of each other and carry similar traffic volumes. The amount of deterioration in each deck at the time of repair was also similar. Two of the structures were repaired by application of a latex-modified concrete overlay, but under different contracts, and the third with a low-slump concrete overlay. Cracks were observed in all the overlays but, coincidentally, the overlay placed in the absence of traffic and 2 yr after the others had the most cracks.

Bridge No. 35404, the only other deteriorated deck to be repaired while traffic was detoured, is also of interest. The structure is located on a curve and has varying degrees of super-elevation resulting in a crossfall as high as 5 percent. The overlay was placed in two operations. The first placement covered the deck except for a 3-ft (1-m) strip adjacent to the barrier wall on the high side of the deck. This strip was placed after the first placement had cured. Although the thickness of the concrete in the strip matched the thickness of the existing concrete at the joint line, there was a difference of approximately 0.25 in. (6 mm) after curing (see Figure B-2). The latex-modified concrete, which was placed at a slump not exceeding 7 in. (180 mm), had flowed toward the low side of the deck after the concrete had been finished and textured. The amount of cracking in the overlay (see Figure B-3) has been estimated to be greater than in any of the other overlays included in the survey, including bridge No. 798 where the cracking is much more extensive than in other structures where the length of cracks has been measured. The data in Table B-4 confirm the results of surveys elsewhere that the amount of deterioration increases with years of service.

TABLE B-4
RESULTS OF SURVEYS OF CONCRETE OVERLAYS IN ONTARIO

| Bridge No. | Year of Overlay | Traffic Maintained | Type of Concrete Overlay | Defect 1977 D[a] | C[b] | 1978 D | C | 1979 D | C | 1980 D | C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 798 | 1978 | Yes | Latex-modified | - | - | - | - | 0 | 1470 | 0 | 1830 |
| 6231 | 1976 | Yes | Latex-modified | Not Recorded | | | | | | 0.22 | 260 |
| 6232 | 1976 | Yes | Low-slump | 0 | 90 | 0 | 100 | 1.31 | 200 | 2.61 | 450 |
| 6233 | 1978 | No | Latex-modified | - | - | 0 | 200 | 0 | 230 | 0.14 | 470 |
| 29196[c] | 1977 | No | Low-slump | - | - | 0 | 30 | 0 | 60 | 0 | 190 |
| 37167 | 1976 | Yes | Low-slump | 0 | 100 | 0 | 200 | 0 | 210 | 0 | 360 |
| 43123[c] | 1976 | No | Low-slump | 0 | 90 | 0 | 90 | 0 | 90 | 0 | 100 |
| 46228 | 1977 | Yes | Low-slump | 0 | 50 | 0 | 110 | 0 | 110 | 0.17 | 100 |
| 46243 | 1977 | Yes | Low-slump | 0 | 25 | 0 | 100 | 0 | 100 | 0.22 | 120 |
| 47002 | 1977 | Yes | Low-slump | 0 | 0 | 0 | 0 | 0 | 60 | 0 | 100 |

[a]Delamination (%).
[b]Cracks ($mm/m^2$).
[c]Bridge new when overlay applied.

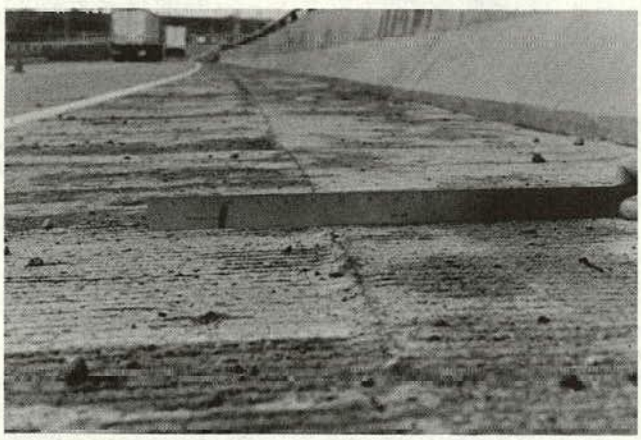

FIGURE B-2 Step at construction joint in latex-modified concrete overlay placed in the absence of traffic.

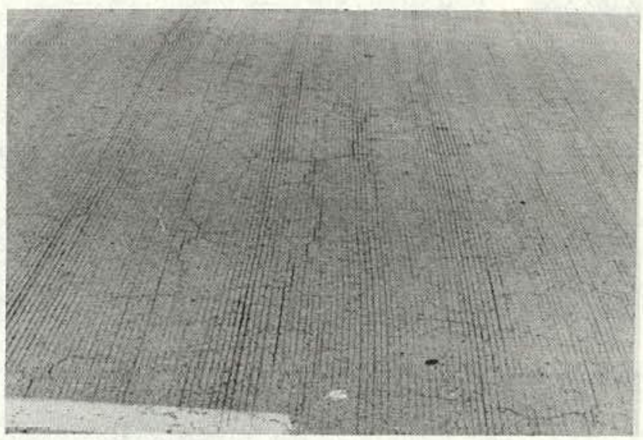

FIGURE B-3 Cracking in latex-modified concrete overlay placed in the absence of traffic.

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RESEARCH SUPERVISOR

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P O BOX 7129 3311 W STATE ST
BOISE ID 83707