# DETERIORATION OF 249 BRIDGE DECKS

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•IN THE PAST decade, highway administrators have recognized the severity of concrete bridge deck deterioration and have requested that serious efforts be made toward solution of the problem. During that same period, largely due to the Interstate Highway program, new concrete bridge decks were constructed at an unparalleled rate in the United States. Already, some of these Interstate highway decks have shown severe deterioration. This paper describes a study of 249 bridge decks built 4 years ago in Pennsylvania. The study was initiated in an attempt to learn the extent of deterioration on fairly new decks and to establish the relative importance of factors commonly associated with deterioration.

The two most important mechanisms of deterioration of concrete bridge decks have been postulated and are generally accepted. These include deterioration by freezing and thawing (6) and spalling caused by corrosion of reinforcing steel (9). Spalling is probably the single most serious form of deterioration from the standpoint of repair cost. It is necessarily preceded by the occurrence of a fracture plane or plane of separation that forms approximately parallel to the traffic surface usually at about the level of the top reinforcing steel. The various phenomena involved in spalling are shown in Figure 1. Note the importance of cracking.

Another type of deterioration, surface wear, is closely related to highway safety. John Volpe, Secretary, U.S. Department of Transportation, named highway safety as one of the six major problems in the transportation field today (10). From a skid resistance standpoint, surface mortar deterioration, particularly wear, is probably the most serious form of deterioration on bridge decks. Traffic wear, aggravated by studded tires (3, 4, 7) polishes the surface, which frequently reduces skid resistance to dangerous levels.

## OBJECTIVES AND SCOPE

The objectives of the study described in the paper were twofold: (a) to discover the extent and nature of deterioration of a large sample of fairly new bridge decks, and (b) to evaluate the relative importance of factors causing deterioration on these decks.

Three major forms of deterioration were considered in this study: spalls and fracture planes; surface mortar deterioration (SMD), including wear by traffic and the general disintegration of weak mortar; and cracking, including transverse, longitudinal, and diagonal. We chose 249 four-year-old decks for observation. Inasmuch as the effects of age have been carefully documented in previous studies, it was excluded as a variable in this study by including only those bridges built in Pennsylvania in 1966. That particular year was chosen because of significant upgrading of Pennsylvania's specifications in the 5-year period prior to 1966. Information from blueprints, construction and maintenance records, and individual contractors was gathered concerning 32 factors (Table 1) that have been related to deterioration by various investigators.

## SURVEY AND ANALYSIS PROCEDURE

### Survey Method

Each of the 249 decks was examined by a 2- or 3-man team. Quantitative measurements of spalled and fractured areas, length of cracks (including only cracks greater

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Figure 1. Spalling phenomena (5).

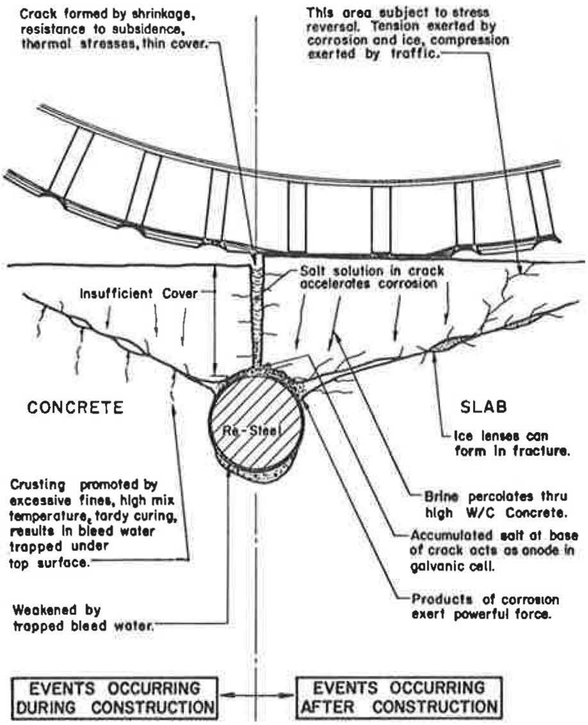


Table 1. Factors related to deterioration.

| Factors | Source | Comments |
|---|---|---|
| Materials | | |
| Average slump | Field construction records | |
| Average air content | Field construction records | |
| Average flexural strength | Actual field test values | |
| Aggregate source | Name of supplier | |
| Use of retarder | | Yes or no |
| Design | | |
| Superstructure type | Final approved designs | Eight types |
| Beam spacing | | Usually 7 to 10 ft |
| Deck width | | Curb to curb |
| Grade of deck | Slope of deck as related to drainage | |
| Skew | Angle of span with roadway | |
| Span length | | Arbitrary minimum of 31 ft |
| Slab thickness | | Usually 8 to 8½ in. |
| Structural stiffness | Calculated with and without parapets for each span | |
| Form type | | Usually stay-in-place or conventionally formed |
| Concrete cover over steel | | Usually specified at 2 in. with an occasional case of 1½ in. |
| Construction | | |
| Contractor | By name | 78 contractors |
| Mixing method | | Central or transit |
| Placement method | | Bucket, conveyor, buggy, or truck |
| Placement temperature | Field temperature data | |
| Month of construction | | |
| Curing method | | Usually wet burlap; sometimes heat and insulation |
| Finishing machine | By name | Seven types |
| Environment | | |
| Average daily traffic | Statewide Statistical Logbook | |
| Maturity period | | Month between end of construction and opening to traffic or de-icing, whichever occurred first |
| ASTM weathering index | (1) | |
| No. of freeze-thaw cycles/year | (1) | |
| Maintenance | | |
| De-icer type | | NaCl, $CaCl_2$, or combinations of the two |
| Rate of de-icer applications | | Usually 200 to 800 lb/mile |
| No. of de-icer applications/year | Individual truck drivers made estimates for their routes | |
| Type of linseed oil applications/year | | Usually 0, 1, or 2 |
| Month of linseed oil applications | | Usually August, September, or October |

than 1 ft long), and areas affected by mortar deterioration were made. Qualitative estimates (visual) of the type and extent of miscellaneous deterioration such as popouts, parapet damage, and others were also made. In cases where spalls occurred, the depth of steel reinforcing was measured with a ruler. Where fracture planes occurred but concrete had not yet become dislodged, a pachometer was used to measure the depth of steel. Steel depth was also measured in sound areas immediately adjacent to deteriorated zones. The deck surveys required about 10 months to complete and were performed between winter seasons.

### Equipment Used

No special equipment was required for the deck surveys other than the aforementioned pachometer and a unique chain drag device used to detect fracture planes (Fig. 2). Although fractured areas are incipient spalls, they are usually not discernible at the road surface even upon close inspection. The chain drag device comprises a timber member with 2-ft lengths of ordinary snow-tire chains attached at 4-in. intervals along the member. As the device is traversed over a fracture plane on the deck, the chains produce a hollow sound. Tape recordings of several of these soundings were quite distinct. When a fracture plane was encountered, it was delineated, and its area and depth to reinforcing steel were measured (Fig. 3).

### Data Analysis

All data, from three major sources (blueprints, questionnaires, and the field survey) as well as from other sources such as contractor interviews, were recorded in a single large logbook. Data from this logbook were punched and verified on computer cards. Five cards were necessary to include all the information for each span of each bridge deck, resulting in approximately 3,000 cards.

The analyses of data were performed in two fashions. First, the data in the logbook were perused for obvious relationships. When one was encountered, e.g., the relationship between certain sources of aggregate and the occurrence of concentrated popouts, it was evaluated by standard statistical techniques. Other relationships that had become obvious during the deck surveys were also evaluated in this manner.

Where relationships between deterioration and its causes were not immediately clear from the data, computer statistical analyses were employed. Because of the large number of possible causes of deck deterioration and the even larger number of possible combinations of interactions of causes, computer analyses were relied on quite heavily. Computer statistical techniques included the Pearson product moment correlation coefficients, upward multiple linear regression analysis, and the automatic interaction detection (AID) technique.

By far the most enlightening data evaluation was achieved with AID (8). Although the results of this study were verified by several statistical techniques, only the AID analysis is discussed in this paper. AID was designed specifically for research problems where the purpose of the analysis is more than the reporting of descriptive statistics but may not necessarily be the exact testing of specific hypotheses. The AID analysis splits variables into two categories based on variance in the dependent variable. It results in a tree diagram that can be easily interpreted for specific details concerning the important factors as well as the interactions of factors. An example of a tree diagram will be presented in the following discussions.

## CONDITION OF THE DECKS

The overall condition of the 249 four-year-old decks was somewhat worse than anticipated. Fracture planes and spalls, the most serious form of deterioration from a repair cost standpoint, were found on 22 percent of the decks. Three decks, each havine very shallow reinforcing steel, were already in need of immediate repair; 11 decks had already been patched to various degrees. Fracture planes and spalls were found in many different positions on the decks. Some appeared to develop preferentially on the shoulders, at joints, and at the beginning or end span.

From the standpoint of skid resistance, wear is the most serious form of deterioration (Fig. 4). Ninety-five percent of these relatively young decks exhibited surface mortar deterioration (wear plus general mortar deterioration), with 97 percent of the affected area attributed to wear and only 3 percent attributed to disintegration of weak mortar (not polished and frequently not in the wheel zones).

In total, about 6.7 miles of cracks were encountered on the 21½ lane-miles of deck surface observed during the study. The distribution of the three types of cracks is shown in Figure 5. Note that, by number and length, transverse cracks occurred more frequently than did other types. In essentially every case, these cracks occurred directly over the transverse reinforcing bars.

Several types of miscellaneous deteriorations were observed to recur frequently. A total of 68.7 percent of the decks exhibited noticeable popouts, and 26.1 percent had one or more areas of severe popouts, indicating aggregate shortcomings. Most of these failures were linked to a few aggregate sources. Map cracking appeared in 20 percent of the decks especially near end spans (possibly related to Pennsylvania's wet-burlap deck-curing specification). There were frequent instances of finishing problems (failure to fully close the surface by screeding) and of debris incorporated in the surface (including mud balls, wires, and very frequently wood chips). Many curbs and parapets exhibited long striations, broken corners, and general disintegration, all of which were thought to have been initiated by snowplows. About 10 percent of the decks had clogged scuppers, and grass was observed growing on the shoulders of two decks.

## RELATIVE IMPORTANCE OF CAUSAL FACTORS

Data collected for the 32 deterioration-related factors (henceforth called causal factors), after being analyzed for obvious relationships, were examined by the AID technique to detect important interactions. Quantitative data for each of the three types of deterioration were analyzed separately and therefore will be described separately in the following sections.

### Fracture Planes and Spalls

Of the 55 decks, 53 exhibiting spalls had insufficient concrete cover (less than the specified design cover) over the reinforcing bars. Although an earlier study (5) had shown 1½ in. to be the critical depth of cover, 1¼ in. appeared to be the critical depth on these 4-year-old decks. The recurrent pattern of spalling associated with insufficient cover speaks poorly for construction practices on these decks.

Of the two decks having spalls where steel depth was adequate, one exhibited delaminations of a latex-modified concrete overlay. The second deck had 12 fracture plane areas, totaling 4½ sq ft, and eight spalls, totaling 10⅞ sq ft. These were distributed in many locations on the deck. The spalls were uniformly ¼ to ½ in. deep (Fig. 6), but the depth of steel in both deteriorated and sound areas was 2½ to 3 in. Many of the smaller fracture planes were at least initiated by patching of the screed rail holes, whereas others appeared to be due to overfinishing. Extensive areas of map cracking (perhaps associated with rapid drying) were also noted on this deck.

Inasmuch as fracture planes are incipient spalls, they were combined with spalls in the AID analysis.

As explained above, insufficient reinforcement cover was detected in nearly all cases where spalls were observed. Unfortunately, due to the large number of decks observed, it was possible to measure steel depth only on decks exhibiting spalls or fracture planes. Therefore, with data only for the deteriorated decks, steel depth could not be included as a variable in the AID analysis. Its importance, however, should be obvious to the reader.

After factors shown to be unimportant in a preliminary AID analysis were deleted, nine remained as predictor causal factors: form type, superstructure type, retarder use, concrete flexural strength, de-icing chemical type, number of salt applications per year, average daily traffic, contractor, and structural stiffness. The effects of these factors on spalls and fracture planes are shown in Figure 7. (Abbreviations used are given in Table 2.) Note that only six of the nine factors were sufficiently

Figure 2. Chain drag device.

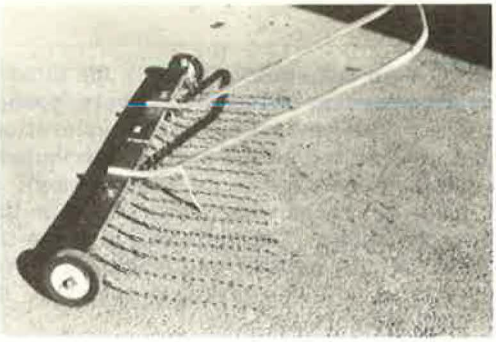


Figure 3. Delineation of fracture plane.

Figure 4. Surface wear deterioration.

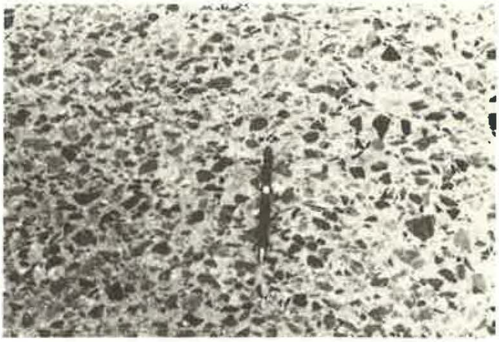


Figure 5. Distribution of types of cracks.

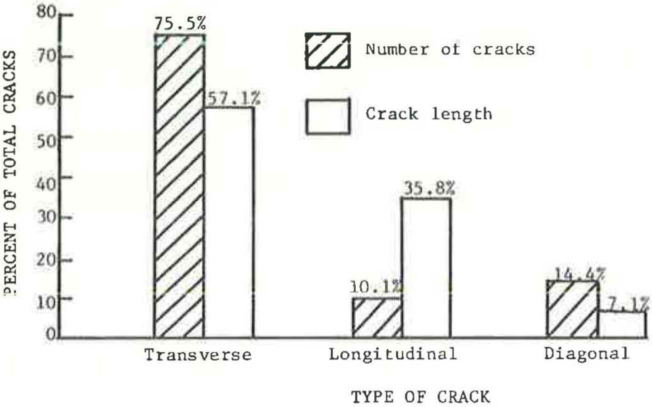
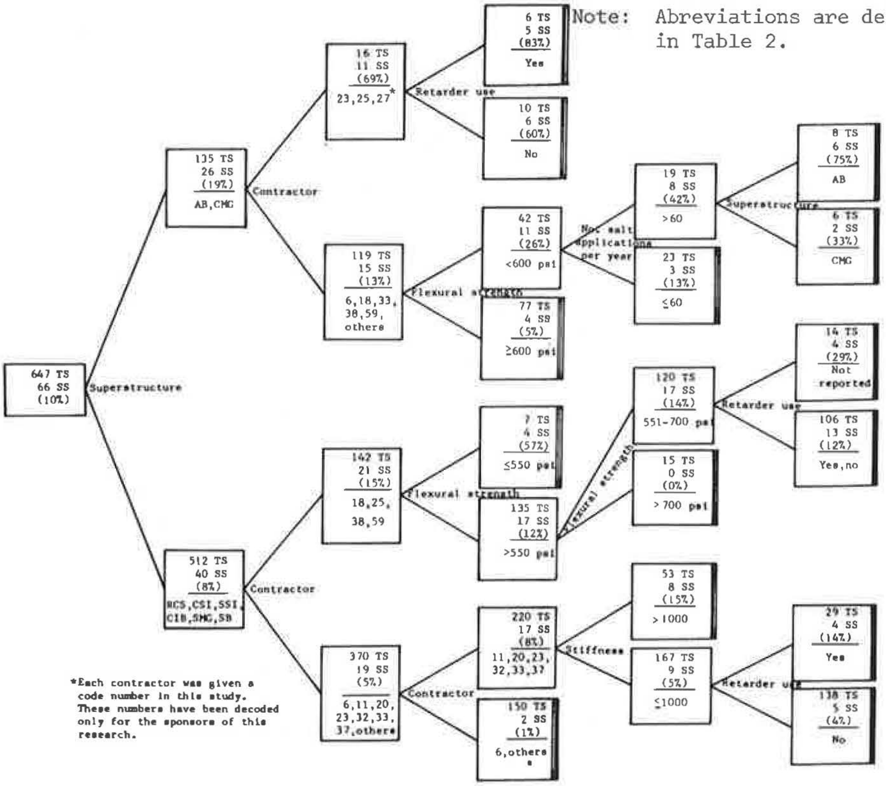


Figure 6. Example of ¼- to ½-in. deep spall.

Figure 7. Effects of six causal factors on spalls and fracture planes.



Note: Abreviations are defined in Table 2.

*Each contractor was given a code number in this study. These numbers have been decoded only for the sponsors of this research.

Table 2. Key to abbreviations.

| Symbol | Definition |
|---|---|
| AB | Adjacent box beam (concrete) superstructure |
| C | Cinders |
| Ca | Calcium chloride |
| CI | Crack intensity (feet of cracks per 100 sq ft of deck) |
| CIB | Concrete I-beam superstructure |
| CMG | Continuous multigirder superstructure |
| CSI | Continuous steel I-beam superstructure |
| CV | Conventional removable (wooden) forms |
| md | Missing data |
| Na | Sodium chloride |
| RCS | Reinforced concrete slab superstructure |
| S | Sand |
| SB | Spread box beam (concrete) superstructure |
| SIP | Stay-in-place forms (metal corrugated forms) |
| SMD | Surface mortar deterioration (percentage of deck area affected) |
| SMG | Simple multigirder superstructure |
| SS | Spalled spans (including fracture planes) |
| SSI | Simple steel I-beam superstructure |
| ST | Crushed stone |
| TS | Total spans |

important to appear on the tree diagram. (The AID program determined that the other three were not able to significantly reduce the unexplained variance.) This diagram for spalls and fracture planes will be explained in detail in the following paragraphs to provide insight into interpretation of the tree diagrams. (Similar tree diagrams for cracks and SMD will not be shown.)

It can be seen from the figure that the most important single variable explaining variation in the occurrence of spalls is superstructure type (recall that it was not possible to include steel depth as a variance). That is to say, of all the possible combinations in each of the nine predictor variables, the grouping of adjacent box and continuous multigirder superstructures against all other superstructures did the best job of explaining whether fracture planes or spalls or both occurred in the 647 total spans, i.e., explaining variance of the data. (Although 813 total spans were surveyed for deterioration, it was not possible to get complete data on each of the 32 causal factors. So we reduced the number of spans to 647 for the fracture plane and spall analysis, 623 for the transverse crack analysis, and 624 for the SMD analysis.) Of 135 adjacent box beams or continuous multigirder spans, 26, or 19 percent, had at least one spall, whereas all other superstructure types exhibited only 40 spalled spans of 512, or 8 percent. The grouping of two types against the remaining six allowed the greatest divergence between occurrences, i.e., 19 percent versus 8 percent. Any other combination of superstructure types would have given less than the 11 percent difference.

Of the 135 adjacent box beam and continuous multigirder spans, 16 spans, of which 69 percent had spalled, were built by only three contractors. Only 15 spalled spans, or 13 percent, occurred on the 119 remaining spans, built by all of the other contractors. Adjacent box beam and continuous multigirder bridges built by the better contractors performed well (about a 5 percent spall occurrence rate) when concrete with a flexural strength greater than 600 psi was used. Lower strength decks spalled more frequently, especially adjacent box beam decks when more than 60 salt applications per year were made. This last analysis is an excellent example of the ability of the AID technique to illustrate the effect of interactions. Of eight spans having adjacent box beam superstructures, greater than 60 salt applications per year, and a flexural strength of less than 600 psi, six spalled.

From the lower branch of the tree, 512 spans were built with superstructures other than adjacent box beams or continuous multigirders. Again, the contractor was the most important single factor associated with fracture planes and spalls. Contractor 6 and "others" (a group of 48 contractors who built fewer than six bridges in 1966) accounted for only two spalled spans out of 150. This excellent performance indicates that bridges resistant to fracture planes and spalls can be built. An intermediate group of contractors, 11, 20, 23, 32, 33, and 37, had 8 percent spall failures, and the poorest group, 18, 25, 38, and 59, had a spall occurrence rate of 15 percent. Among the spans constructed by the poorer contractors, four of seven with flexural test values of 500 psi or less exhibited spalls. It is also significant to note that no span having a flexural test strength greater than 700 psi spalled even though built by the poorer group of contractors. This speaks strongly for higher strength concrete (low water content or high cement factor or both) for bridge decks. The influence of retarder use on the 120 intermediate strength spans appears minimal, inasmuch as the AID program grouped "yes" and "no" against "not reported."

In the lowermost branch of the tree, of the 220 spans with 8 percent exhibiting spalls, stiffness appeared to correlate inversely to what one would expect. High stiffness should reduce flexibility and thus cracking, thereby reducing spall occurrence. In this analysis, however, very stiff spans appear to exhibit somewhat more spalling. A separate analysis on the entire 813 spans showed no significant correlation between stiffness and cracking at the 95 percent confidence level (2).

Retarder use appeared three times in the entire analysis. As stated previously for the group of spans having high flexural strength, retarder use was not a significant factor. However, in two of the three cases, there appeared to be a slight disadvantage to the use of a retarder.

Form type, de-icing chemical type, and average daily traffic did not appear as important factors in this analysis of spalling. Without question, superstructure type, contractor, and flexural strength are the primary factors controlling whether fracture planes and spalls occur. Unfortunately, the decisions to use adjacent box beam and continuous multigirder superstructures are usually dictated by physical constraints and are not subject to change. However, flexural strength can be altered by specification, and construction practices, as indicated by the contractor variable in this study, can and should be closely regulated. These analyses clearly show that, under the same specifications and at the same time, different contractors can produce durable and nondurable bridge decks.

### Cracking

Similar analyses performed on crack data resulted in another tree diagram, shown in Figure 8. Although detailed interpretation of this analysis is left to the reader, note that again several variables proved important: contractor, form type (stay-in-place metal corrugated or conventional removable wooden forms), superstructure type, span length, and others.

### Surface Mortar Deterioration

The surface mortar deterioration tree diagram is shown in Figure 9. Again the importance of the variable contractor is evident as is form type, different antiskid materials, average daily traffic, and others.

## CONCLUSIONS

As stated earlier, one of the twofold objectives of the investigation was to provide a condition report of a large sample of fairly new bridges. A brief summary of the condition of the decks is presented in an earlier section of this paper [for a more detailed condition report, see Cady et al. (1)].

All of the causes of deterioration investigated in connection with the second objective are generally recognized today. Indeed, we chose to evaluate known causes of deterioration on a large sample of bridges in an attempt to determine the relative importance of these causes; for, although these causes of deterioration have been recognized for some time, we continue to experience inadequate deck performance.

Table 3 gives a summary of those factors that appeared most strongly related to deterioration in order of decreasing importance. Note the relationship between construction practices and all three major forms of deterioration. This suggests that improved inspection and quality control at the jobsite would yield maximum benefit, particularly with regard to providing adequate concrete cover.

## RECOMMENDATIONS

It is hoped that the information presented will allow policy and procedural changes to be directed toward elimination of the most serious causes of deterioration. Whereas some of the factors in Table 2 such as average daily traffic, de-icer usage, and superstructure type are constraints generally outside the control of engineers, two very strong relationships suggest changes that could be made.

For these study bridges, early spalling was almost always associated with inadequate concrete cover. Provision of sufficient cover is absolutely essential to durable bridge decks. The authors, therefore, recommend that provision of the specified cover be made a basis-of-payment item, similar to the slab thickness basis-of-payment for highway pavements. Also, in view of the improved performance of high-strength decks, the authors recommend that flexural strength requirements be increased to 700 psi for bridge deck concrete.

## ACKNOWLEDGMENTS

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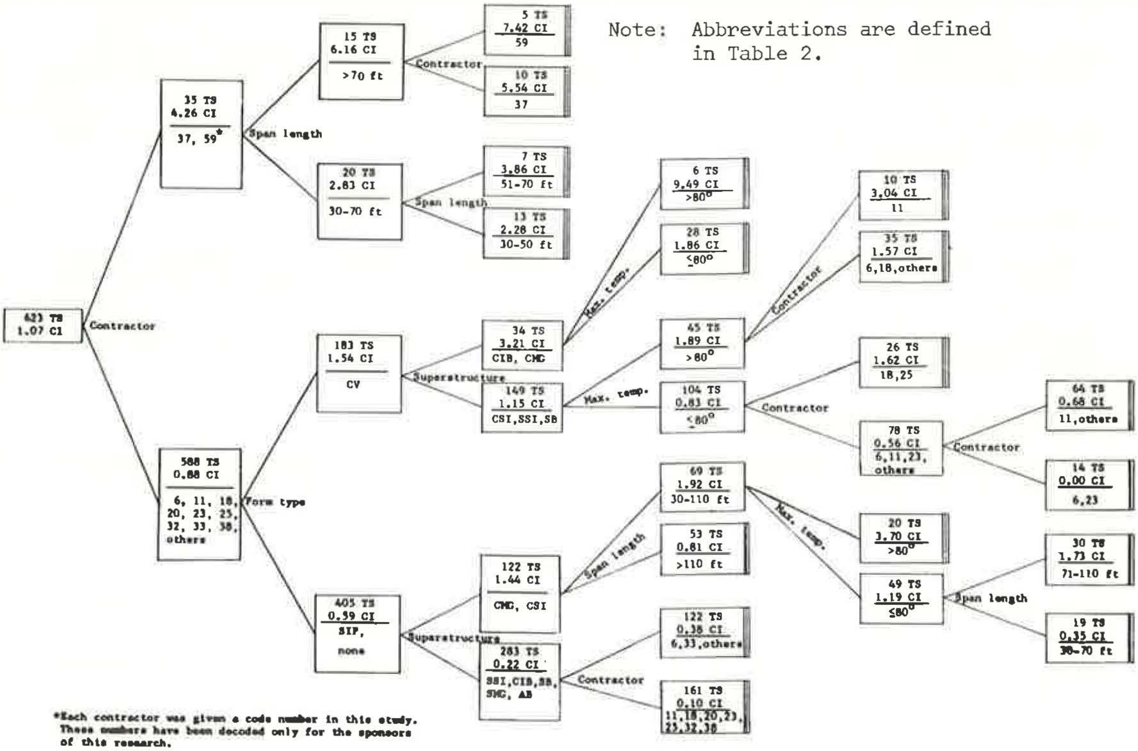
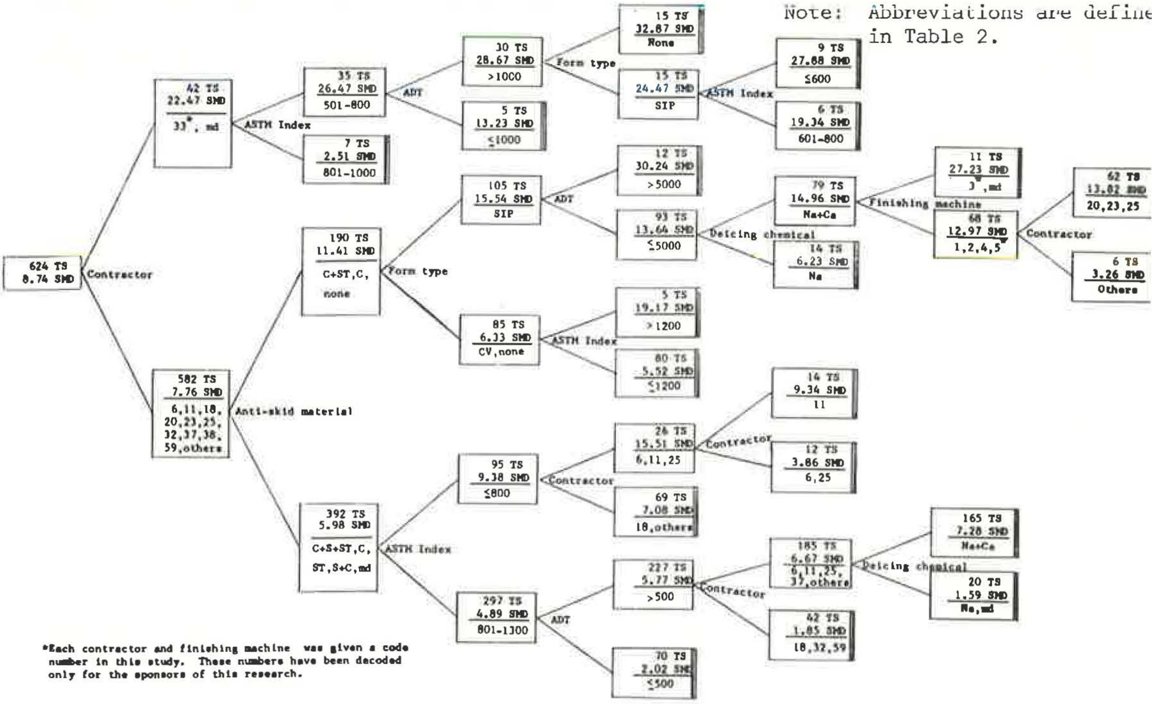
Figure 8. Effects of five causal factors on crack intensity.



Note: Abbreviations are defined in Table 2.

*Each contractor was given a code number in this study. These numbers have been decoded only for the sponsors of this research.

Figure 9. Effects of seven causal factors on surface mortar deterioration.



Note: Abbreviations are define in Table 2.

*Each contractor and finishing machine was given a code number in this study. These numbers have been decoded only for the sponsors of this research.

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Page 55, in the Discussion by Chamberlin, Amsler, and Jaqueway, after the text table, insert the following: Data are in linear feet of transverse cracks per 100 $ft^2$ of bridge deck.

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## DISCUSSION

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The authors' observation on the association of major defects with the use or nonuse of corrugated metal stay-in-place (SIP) forms is welcome, particularly in view of the strong opinions that the subject evokes in the absence of factual information.

They have shown that 4-year-old, SIP-formed decks in Pennsylvania have far fewer transverse cracks than conventionally formed decks of the same age but that they exhibit somewhat more deterioration of surface mortar, primarily in the form of wear. They conclude from this evidence that form type is an important determinant of both transverse crack intensity and surface mortar deterioration.

A recent study of the condition of 716 bridge decks in New York State (11) supports the authors' findings with regard to the association of lesser transverse crack intensity with the use of SIP forms. Data given below show that SIP-formed decks in New York have less than one-half the amount of cracking of those formed by conventional methods.

| Source | SIP | Conventional |
|---|---|---|
| (1) | 0.46 | 1.50 |
| (11) | 0.55 | 1.27 |

The New York study includes most decks built in the state during the 7-year period, 1965 to 1971—about one-half with SIP forms (Fig. 10).

The lesser crack intensity found in SIP-formed decks in New York appears to result from a combination of two circumstances (Table 4): (a) substantially fewer cracked spans and (b) substantially fewer cracks in those spans that are cracked.

Table 3. Major forms of deterioration and their causes.

| Type of Deterioration | Cause |
|---|---|
| Fracture planes and spalls | Depth of steel, superstructure type, construction practices, flexural strength, retarder use, number of salt applications per year |
| Cracks | Construction practices, form type, span length, superstructure type, maximum placement temperature |
| Surface mortar | Construction practices (especially finishing), antiskid material (may be related to use of $CaCl_2$ on stock piles), form type, average daily traffic, de-icing chemical type, finishing machine |
| Miscellaneous | Difference in elevation of approach slab and deck as related to broken slab edges, aggregate sources as related to popouts, snowplow damage as related to parapet deterioration |

Figure 10. Distribution of SIP-formed decks in New York.

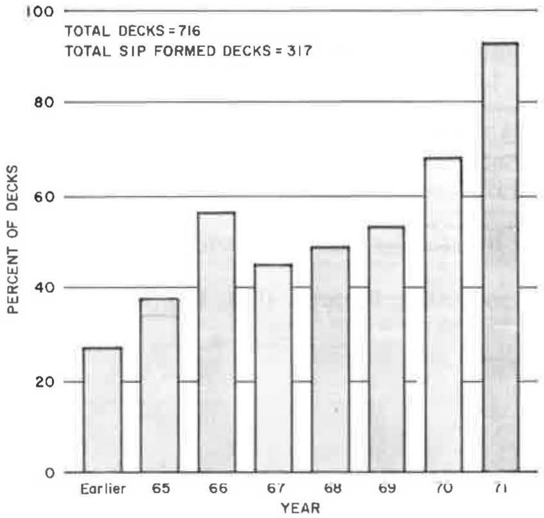

Figure 11. Frequency of transverse cracking by year of construction.

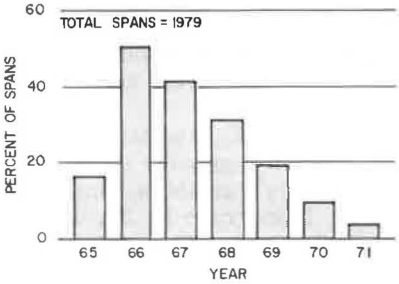

Table 4. Transverse cracks in New York bridge decks.

| Feature | Forming Method: SIP | Forming Method: Conventional |
|---|---|---|
| Proportion of spans cracked, percent | 22.1 | 32.9 |
| Cracks per 100 sq ft of cracked span | 0.22 | 0.35 |
| Mean crack length, ft | 11.5 | 11.2 |

Although it is tempting to infer a cause-and-effect relationship between deck cracking and forming method, on the basis of the association observed between these two factors, it is perhaps premature without either more statistical evidence to support the authors' finding or a better understanding of the mechanism through which the two observations are related or both. With regard to these deficiencies, the New York results do not wholly support the authors' conclusion of a causal relationship.

The New York experience appears at first glance to supply the additional statistical evidence. Yet the lower crack intensity in SIP-formed decks in New York also can be explained by factors other than forming method. As shown in Figure 10, SIP-formed decks in New York, as a group, are younger than those formed by conventional methods. This fact, combined with the strong age-dependence of transverse cracks (Fig. 11), supplies an alternate explanation for the higher crack intensity associated with conventionally formed decks; i.e., conventionally formed decks are cracked more intensely because more are older. Unfortunately (for this purpose) the objectives of the New York survey were primarily descriptive, and the information at hand does not permit a more exhaustive study of causal factors, which might resolve this question. The Pennsylvania study, of course, was confined to decks of the same approximate age and does not suffer from this dilemma.

Regarding mechanisms, the authors (1) have speculated that the lesser crack intensity associated with the use of SIP forms could result from slower water loss in the fresh concrete with more gradual shrinkage or increased stiffness of the deck due to composite action. If this water-loss hypothesis is true, then cracking associated with forming method probably occurs early in deck life when drying (and shrinkage) is more rapid and strength not fully developed. However, this seems contrary to the implication of Figure 11, and to the findings of other investigators of bridge deck cracking (12), that the occurrence of transverse cracks is age-dependent. Resolution of this matter may rest on the question of whether transverse cracks resulting from such causes really become more frequent with deck age or develop early and just become more apparent with age.

Our point in this discussion is that the association of SIP-formed decks with lower transverse crack frequencies, observed by the authors in Pennsylvania, is supported by experience in New York but that the acceptance of a cause-and-effect relationship between the two should await additional statistical support or a better understanding than is now available of the particular circumstances under which form-related bridge deck cracks occur.

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