STUDIES OF THE RELATIONSHIPS AMONG CRACK PATTERNS, COVER OVER REINFORCING STEEL, AND DEVELOPMENT OF SURFACE SPALLS IN BRIDGE DECKS

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Surface spalling is probably the most serious bridge deck durability problem today. Previous investigations suggest that corrosion of reinforcing steel in the presence of salt solutions is basically responsible for this type of deterioration. In a cooperative bridge deck study, an examination was made of the relationships among the development of spalls, the nature of the crack pattern, and the cover over reinforcing steel. Based on the results of this work, it is hypothesized that the crack pattern on a bridge deck greatly influences the development of spalls, and that the crack pattern is, under a given set of conditions, determined to a great extent by the amount of cover over the reinforcing steel. Where cracks develop directly over reinforcing steel, salt solutions have relatively easy access to the steel, thereby accelerating corrosion and the development of spalls. It is suggested that by limiting the cover to a minimum of 2 in. and by utilizing coarse aggregates of low porosity and compressibility and the lowest water-cement ratio feasible, the amount and severity of cracking over steel will be reduced. The ease with which salt solutions can migrate to the reinforcing steel will also be lessened.

The durability of concrete bridge decks is affected primarily by 2 types of deterioration—surface scaling and spalling associated with reinforcing steel. The means for preventing surface scaling is fairly well understood, but a number of questions remain regarding the problem of spalling. This paper summarizes the influence of one aspect of this problem—the effect of concrete cover over reinforcing steel on the development of spalls.

NATURE OF SPALLS

A surface spall is manifested in the removal of an inverted, more or less conical or trough-like piece of concrete, the apex of which extends to the upper surface of the top reinforcing steel, as shown in Figure 1. Numerous cores taken through spalls and incipient spalls revealed the occurrence of a layer of steel corrosion products at the apex of the spall, as shown in Figure 2. In addition, a generally vertical crack was observed that extended from the wearing surface downward to the reinforcing steel. Most commonly this crack passed through aggregate particles and was lined with corrosion products in the vicinity of the steel bar.

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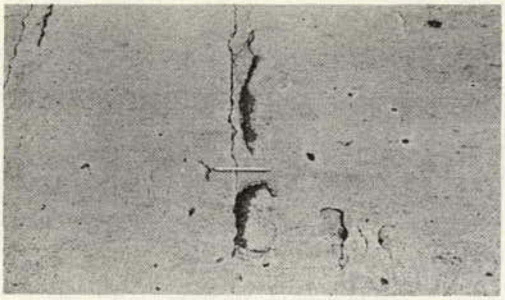

Figure 1. Typical surface spall associated with reinforcing steel.

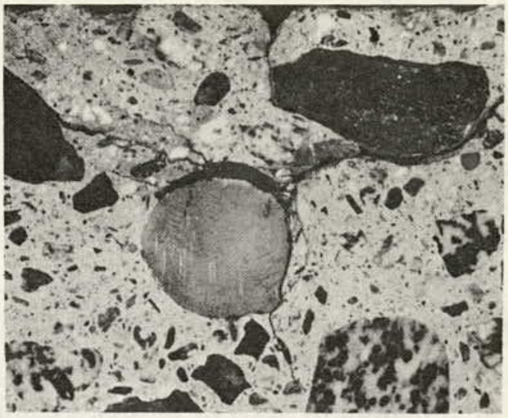

Figure 2. Cross section of reinforcing steel and part of surface spall showing cracking and associated corrosion of steel at upper surface.

Spalls of this type have a comparatively high frequency of occurrence but affect a relatively small percentage of the wearing surface of bridge decks. They generally occur in clusters and show no regular geometric occurrence with bridge deck design. This problem was reported to have become critical since the use of de-icers and is most severe in freeze-thaw areas where de-icer salts are applied. Numerous analyses (1, 2, 3, 4) of cores taken from bridge decks indeed revealed greater concentrations of chloride ions in the vicinity of top reinforcing steel in sound cores taken from spalled decks than in sound cores taken from nonspalled decks, as shown in Figure 3. However, spalling has also been observed, to a much lesser extent, in bridge decks exposed to salt sprays, such as near oceans, where there is no freezing and thawing (3). These circumstances therefore suggest that spalling is caused by corrosion of the reinforcing steel by salt solutions and that freezing and thawing per se is not a requirement for its development but may aggravate the situation by generating stresses in addition to those produced through electrochemical reactions in the steel.

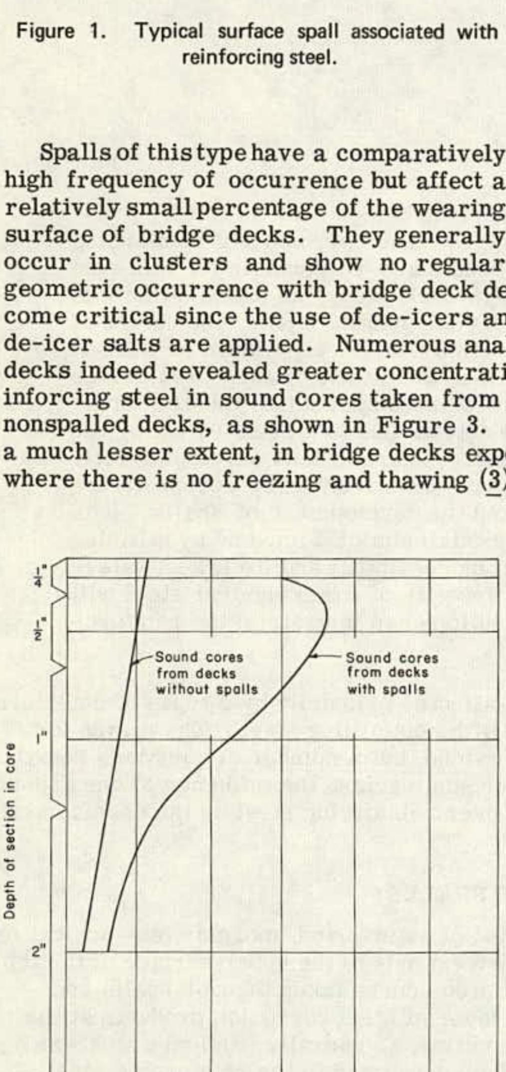

Figure 3. Average chloride distribution for sound cores from spalled and nonspalled decks.

Based on the cooperative bridge deck studies (1, 2, 3, 4), the presence of a vertical crack extending from the wearing surface to the reinforcing steel appeared to have a strong association with this type of deterioration. A compilation of findings in these cooperative studies, given in Table 1, indicates several relationships between spalling and cracking. These data show that surface spalls were wholly confined to areas containing cracks directly over top reinforcing steel. Fewer spans containing pattern or random cracks as well as cracks over top steel also contained surface spalls. In no span were spalls associated only with pattern or random cracks, nor did they occur where there were no visible cracks. Petrographic examination of cores taken from these decks also revealed an association between spalls and the presence of vertical cracks extending downward to the top reinforcing steel.

These findings would seem logical because the crack would provide more rapid access of de-icer solutions to the reinforcing steel. This, however, does not preclude the possibility of salt solutions migrating through sound concrete to the reinforcing steel, thereby causing the development of spall. Evidence of this possibility is suggested in the recent work by Spellman and Stratfull (5). Although differential subsidence of plastic concrete above and between the top reinforcing bars may play a role in the development of spalls, in the bridges studied and described in this report this did not appear to be of importance. This is also suggested by the relative scarcity or absence of spalls in many older decks compared with what must be essentially the universal occurrence of differential subsidence phenomena. In addition, petrographic evidence of these phenomena was totally lacking in cores taken through spalls and in any core taken in spans containing spalls.

TABLE 1

CONDITION OF DECK WEARING SURFACE

Condition	Percent of Spans With Condition
No cracking or surface spalls	17.0
Cracks directly over top steel only	30.0
Cracks directly over top steel plus surface spalls	22.0
Pattern and/or random cracks only	7.9
Pattern and/or random cracks plus surface spalls	0.0
Pattern and/or random cracks plus cracks directly over top steel	17.0
Pattern and/or random cracks plus cracks directly over top steel plus surface spalls	6.3
Spalls only	0.0

FIELD STUDIES

The crux of the problem therefore appears to center on the accessibility of salt solutions to the reinforcing steel. Of prime importance is the nature of the existing crack pattern and the amount of cover over the top steel. Studies were therefore made of 7 decks in Michigan (2) in order to more fully evaluate the significance of these factors. For measuring the amount of cover over top steel, 2 pachometers were used. Each of these devices is battery operated and consists essentially of a transistorized oscillator that establishes an electromagnetic field in a search coil. When the search coil is brought into the vicinity of the reinforcing steel, the magnetic field becomes distorted. At maximum distortion the bar is parallel to the axis of the search coil. By previous calibration, the distance from the bar can be read directly from the meter dial. One of the pachometers was used for measuring cover less than $1\frac{5}{8}$ in., while the other (larger) device was used for measuring cover between $1\frac{5}{8}$ in. and a practical maximum of $4\frac{3}{4}$ in. Figure 4 shows the procedure used in determining the cover over the top reinforcing steel. A record was also kept of the occurrence of vertical cracks over top reinforcing steel.

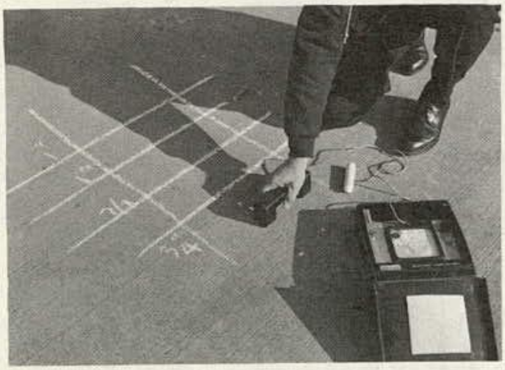

Figure 4. Use of pachometer in measuring cover over steel on bridge deck.

RESULTS OF THE INVESTIGATION

Data obtained in this work were plotted on schematic drawings of the bridge decks, in which the occurrence of spalls and transverse cracks are noted, together with the position of the piers. Figures 5, 6, 7, and 8 show typical results obtained.

The bridge deck shown in Figure 5 was 11 years old at the time the measurements were made; the specified cover was $1\frac{1}{8}$ in. Measurements in one of the few spalled areas showed cover ranging from $1\frac{1}{4}$ to $\frac{3}{4}$ in. The spalls occurred where the cover was 1 in. or less. Spot checks elsewhere revealed that the cover varied from $1\frac{11}{16}$ to $2\frac{1}{4}$ in. In these areas there was a total absence of spalls and incipient spalls

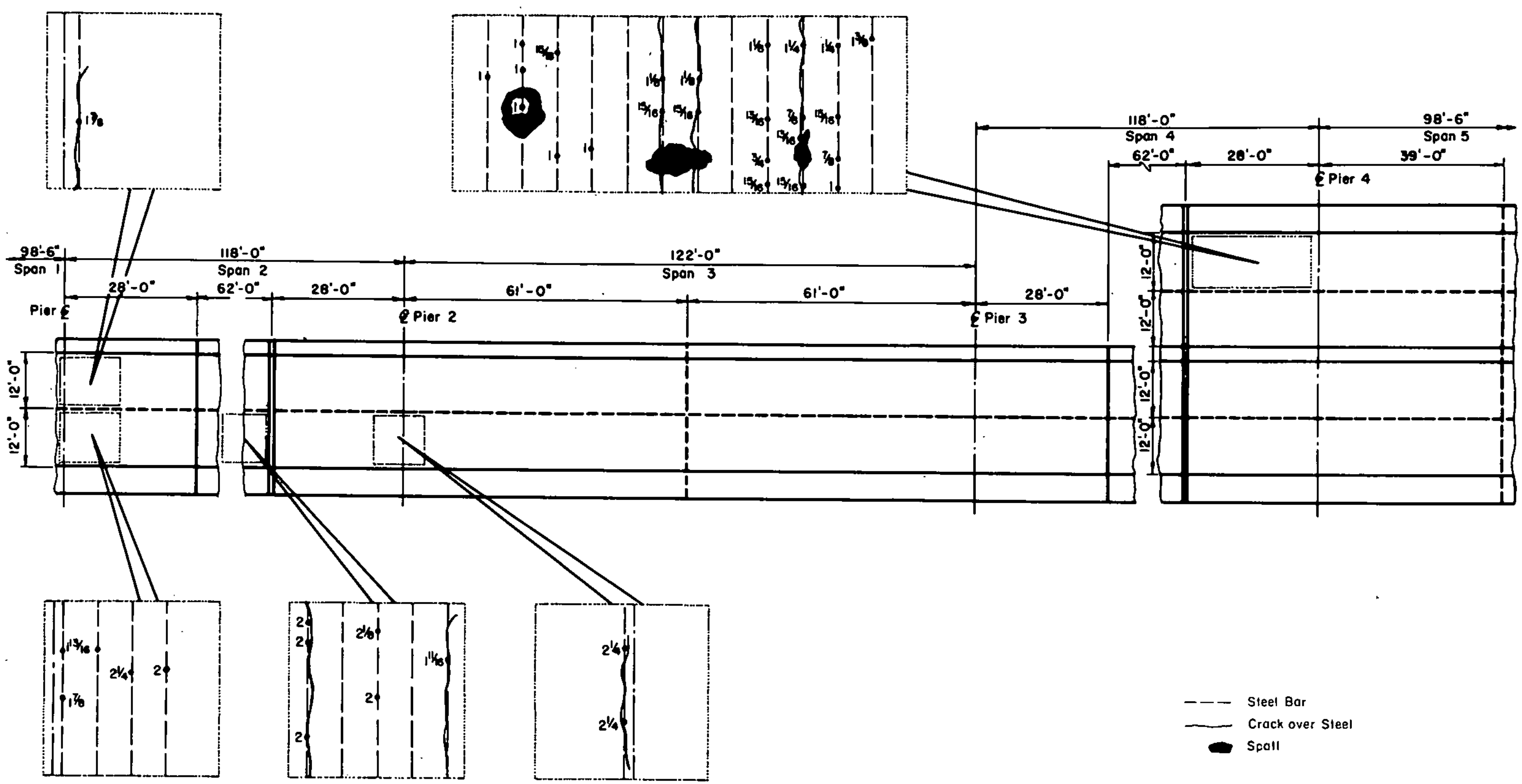

Figure 5. Results of measurements of cover over top steel in 5-year-old bridge deck with specified 1⅛-in. cover (cover, in inches, is shown adjacent to steel bar).

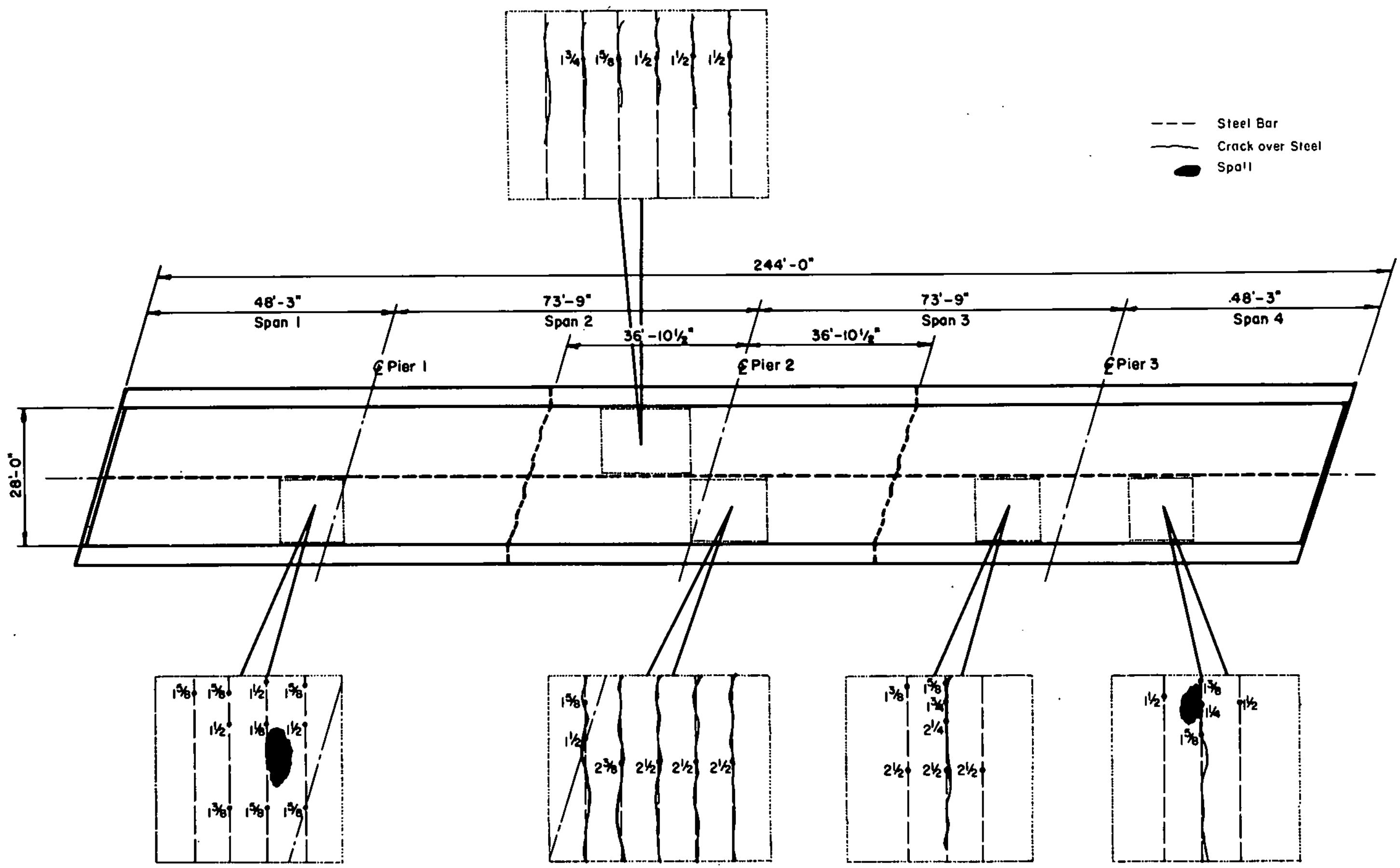

Figure 6. Results of measurements of cover over top steel in 7-year-old bridge deck with specified 1½-in. cover (cover, in inches, is shown adjacent to steel bar).

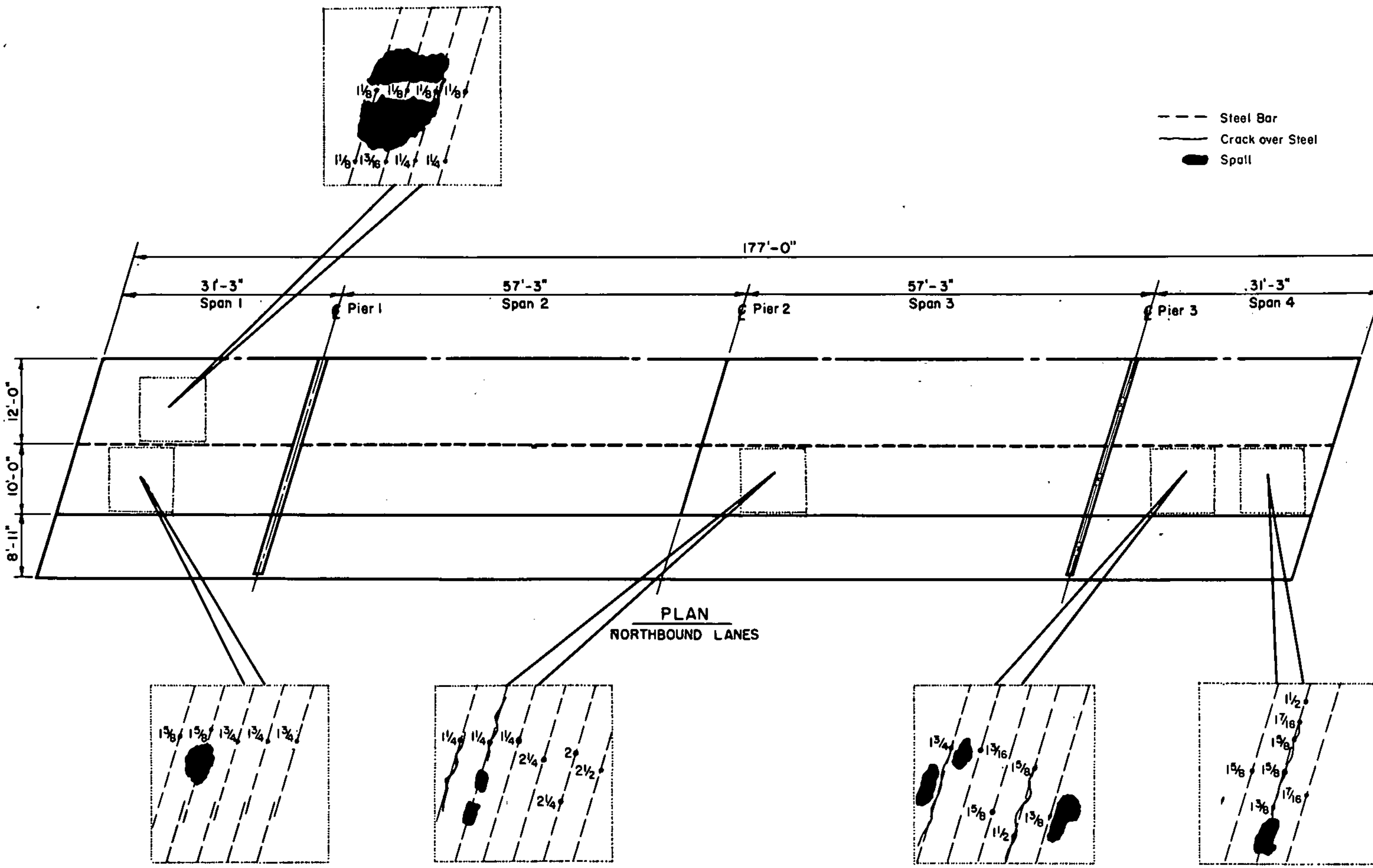

Figure 7. Results of measurements of cover over top steel in 14-year-old bridge deck with specified 1⅛-in. cover (cover, in inches, is shown adjacent to steel bar).

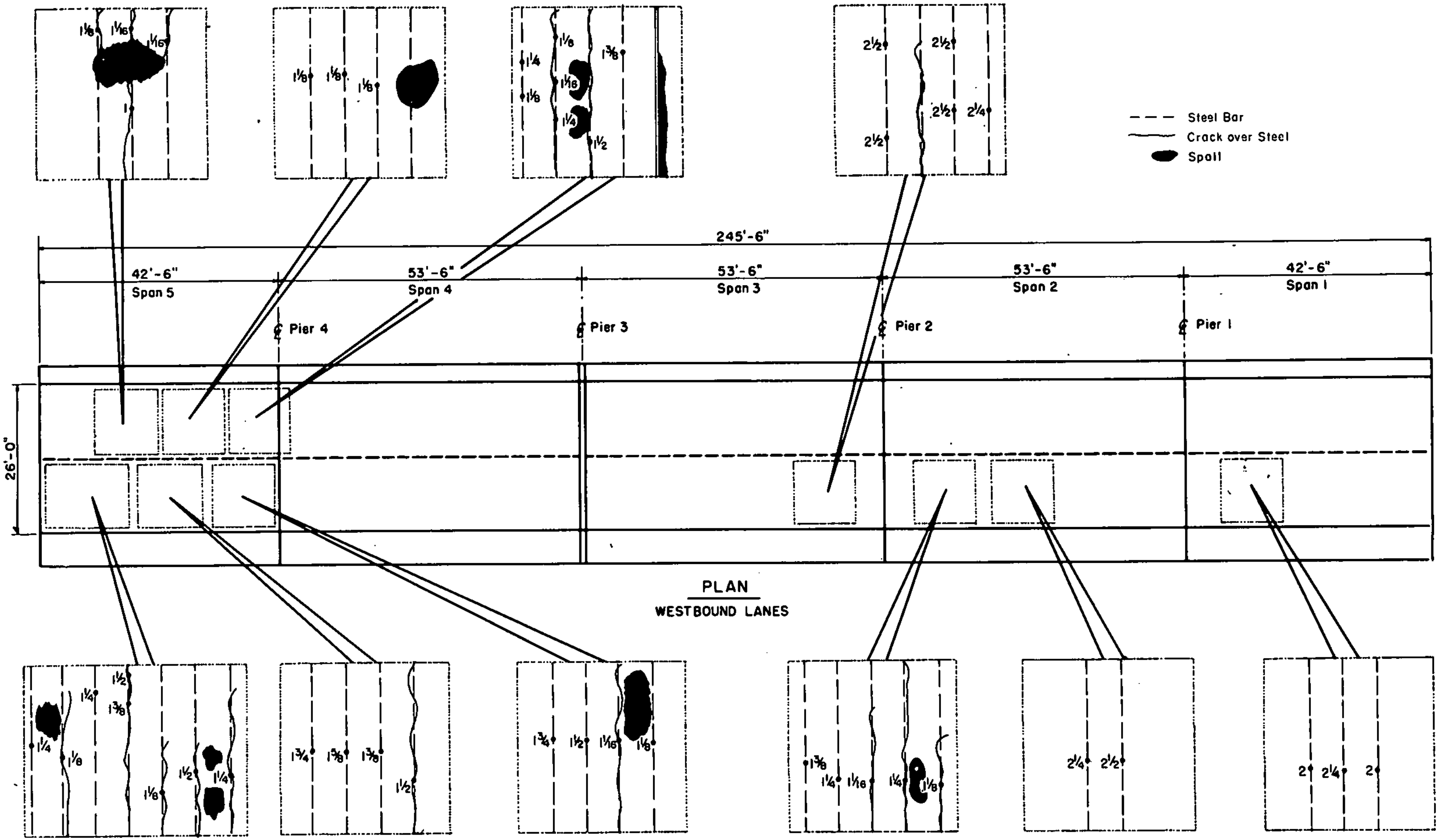

Figure 8. Results of measurements of cover over top steel in 7-year-old bridge deck with specified 1⅛-in. cover (cover, in inches, is shown adjacent to steel bar).

but a well-developed system of pattern cracks and a few tight transverse cracks. These pattern cracks were not associated with progressive deterioration.

Figure 6 shows the results for a 7-year-old deck with a specified cover of 1½ in. The actual cover was found to vary from 1⅛ to 2½ in. Only 2 spalls occurred in this deck, and both were associated with a cover of 1⅛ to 1⅝ in. Numerous faint transverse cracks were observed over the entire deck with the cover ranging from 1⅝ to 2½ in. Also, there were relatively large areas free of visible cracks where the cover ranged from 1⅜ to 2½ in.

Figure 7 shows a 14-year-old deck with a specified cover of 1⅛ in. Spalling occurred over most of the deck and was located in areas where the cover varied from 1¼ to 1¾ in. On the bridge as a whole, there was a noticeable lack of vertical cracks directly over steel, but in areas where they did occur spalls and incipient spalls were invariably present. Spot checks in areas where there were no cracks indicated cover of 1¾ to 2½ in.

Figure 8 shows a 7-year-old deck with a specified cover of 1⅛ in. Spalls and incipient spalls were found in 3 of the 5 spans in this deck. All spalls were associated with reinforcing steel with a cover ranging from 1 to 1½ in. Transverse cracks occurred over steel with a maximum cover of 1½ in. Many areas of the deck displayed only faint pattern cracking, and in these areas the cover was 2 to 2½ in. Again, there was no progressive deterioration associated with these cracks.

Measurements made on the other decks not specifically reported here revealed substantially the same relationships. That is, spalls were found associated with transverse cracks in areas where cover over steel was less than 2 in. Also, pattern or random cracks or both predominated in cracked areas where the cover over steel was greater than 2 in.

DISCUSSION OF RESULTS

Several relationships have been found in these studies that point to circumstances leading to the development of surface spalls and to methods of delaying this problem. First, a correlation was found in the field measurements between the amount of cover over top reinforcing steel and the occurrence of surface spalls. Measurements revealed that all spalls were associated with reinforcing steel with less than 2 in. of cover; usually, the cover was less than 1½ in. Numerous areas with 2 in. or more were found adjacent to areas with less than 1½ in. of cover, yet spalls occurred only in areas with the lesser amounts of cover. This finding was valid even for 1 deck more than 14 years old. Petrographic examination of numerous cores from other states in the cooperative studies also revealed that spalls and incipient spalls were associated only with steel having less than 2 in. of cover.

A second relationship was found between the occurrence of spalls and incipient spalls and the nature of the crack pattern. Without exception, spalls occurred only in areas where vertical cracks occurred directly over top reinforcing steel. In areas where only pattern or random cracks, or no cracks, were reported, there was a total absence of spalls. In some areas, spalls were found where pattern or random cracks occurred together with cracks directly over the top steel, but they were associated only with cracks of the latter type.

A third relationship was found between the nature of the crack pattern and the amount of cover over top steel. Where the cover was less than 2 in., the crack pattern consisted primarily of cracks directly over top steel; but where there was more than 2 in. of cover, random or pattern cracking was most often found. The change from one crack pattern to the other was not abrupt, and in many cases one pattern did not occur exclusive of the other.

These relationships suggest an explanation for the occurrence of spalls where the cover over top steel is less than about 2 in. or, conversely, the absence of spalls where the cover is more than about 2 in. Where the cover is less, vertical cracks will tend to form more readily over the top steel, thereby providing ready access of de-icer solutions to the steel. Where there is more than about 2 in. of cover, pattern or random cracks tend to develop. These cracks do not follow the position of the reinforcing steel and would not provide ready access of de-icer solutions to the steel. Thus, under given conditions, the development of spalls appears to depend greatly on the amount of cover over the steel, which in turn influences the nature of the crack pattern and the consequent accessibility of de-icer solutions to the reinforcing steel. If vertical cracks do form and extend to the top steel where the cover is greater than approximately 2 in., as shown in Figures 5 and 6, susceptibility of the concrete to spalling is correspondingly increased. On the other hand, cracks will not necessarily form directly over top steel even where the cover is appreciably less than 2 in.

These explanations concerning the interplay of crack patterns, cover over steel, and development of spalls presupposes a given set of conditions and materials. Both factors, i.e., climate and materials, would appear to affect these relationships. Severe climatic exposures, such as prolonged drying conditions at high temperatures, for example, would tend to widen cracks over steel because of resistance to shrinkage of the hardened concrete, thereby permitting easier access of de-icer solution to the steel. The use of pastes having low water-cement ratios and aggregates having low porosity and compressibility would result in minimum potential drying shrinkage and fewer, tighter cracks over steel. Where severe exposures are anticipated and the conditions for spalling are likely, it would be beneficial to utilize concrete of the lowest shrinkage potential possible and design the deck reinforcement so as to reduce the extent and severity of cracking directly over top reinforcing steel.

ACKNOWLEDGMENT

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