Concrete-Deck Deterioration: Concrete-Filled Steel-Grid Bridge Decks Have the Answer

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The most common cause of bridge-deck distress is the corrosion of the reinforcing steel that results from the intrusion of chlorides into the concrete after repeated deicer applications. However, there are many concrete-filled steel-grid bridge decks in existence that have not been affected by deicing chemicals, although the amount of chloride present is significant and sufficient to initiate steel corrosion. Data on more than about 400 000 m^2 (4 000 000 ft^2) of grid decks built between 1931 and 1969 showed that the performance of such decks has been excellent. The soundness of the concrete has not been affected, and the steel within the concrete shows no rust or corrosion. These decks have withstood severe weather conditions and frequent use of deicing chemicals. The satisfactory condition of these grid decks, in service for over 40 years, is significant evidence of their durability, which has been accomplished without the help of waterproofing membranes, coatings on steel, cathodic protection, or other treatments designed to prolong bridge-deck life.

The deterioration of reinforced-concrete bridge decks is well known to highway bridge designers and maintenance engineers. The Office of Research and Development of the Federal Highway Administration considers that the elimination of bridge-deck deterioration deserves a high priority effort (1). It is generally believed that the most common cause of bridge-deck distress is the corrosion of the reinforcing steel that results from the intrusion of chlorides into the concrete after repeated deicer applications (2, 3, 4, 5). Most research on bridge-deck deterioration has been directed at stopping or abating the intrusion of chlorides into the concrete.

There has been very little or no research on types of deck systems that are not significantly affected by chlorides. One such system is that of steel-grid construction filled with concrete.

The purpose of this paper is to draw attention to the existence of grid systems that have performed well for over 40 years and are still in sound structural condition. An investigation of more than 400 000 m^2 (4 000 000 ft^2) of such decking on bridges built between 1931 and 1969 showed that concrete-filled steel-grid decks have withstood heavy traffic under severe weather conditions (6).

Physical examination of these decks showed that there was no sign of distress and that the concrete was in sound condition. The chloride concentrations found in some of these decks are sufficient to initiate corrosion of the steel grid. However, none of the decks tested showed any surface spalling or corrosion (7).

The durability of concrete-filled steel-grid decks in a chloride-containing environment is illustrated by one of the smallest bridges investigated (Figure 1), which has a deck area of 43 m^2 (468 ft^2). This bridge deck has been in service for 42 years. It has a mean chloride concentration of 6.22 kg/m^3 (10.49 lb/yd^3) of concrete, but no physical damage or deterioration is noticeable. The deck was built with concrete finished flush with the top of the grid steel, and no wearing surface was ever applied. The surface condition of the deck is shown in Figure 2, in which the heavy lines are the exposed top flanges of the main beams of the steel grid, and the lines perpendicular to them are the tops of the rectangular cross bars. This surface condition is typical for grid decks where no wearing surface was ever used.

PERFORMANCE OF EXISTING CONCRETE-FILLED STEEL-GRID DECKS

Information on the condition of 17 existing concrete-filled steel-grid bridge decks was obtained from the engineers responsible for their maintenance and is summarized in Table 1. These decks have been in service for 12 to 44 years. The history of their performance has been excellent. The soundness of the concrete has not been affected, and the steel within the concrete shows no significant corrosion. However, bridges 11 and 12 have not performed well. On these two bridges, the design did not specify an adequate amount of welding of the grid to the supports and the transverse reinforcement was not sufficient. These decks have had maintenance problems due to broken welds at the supports. The broken welds have had to be repaired, but the decks are still in service.

In general, concrete-filled steel-grid decks have been designed according to the AASHO specifications for highway bridges (8). These specifications do not provide for adequate transverse steel or welding of grids to supports. A review of the design and construction details of the 17 bridges showed certain differences that have influenced the performances of the decks.

CONSTRUCTION OF CONCRETE-FILLED STEEL-GRID DECKS

Steel-Grid Floor System

The typical construction details of a steel-grid floor system are shown in Figures 3 and 4. The system consists of the main load-carrying members (usually rolled I-sections), top and bottom cross bars placed at right angles to the main bars, and metal form pans that are tack-welded to the bottom flanges of the main I-sections to retain the concrete. The grid floor is factory assembled—usually in panels 2.4 m (8 ft) wide and up to 14.6 m (48 ft) long. These panels are then transported to the bridge site and installed on the supports designed to carry the deck to create a working platform for further work such as splicing, bolting, welding, and building expansion dams. No field formwork is required because the metal form pans are already provided. After the miscellaneous work is performed, the concrete is poured and cured according to standard practices. The grid panels can also be precast with concrete if necessary.

The materials used in the construction of grid decks are usually, as specified by ASTM, A7, A7 (0.2 percent copper), A36, or A588 steels.

Grid Beams and Main Members

Specially rolled I-sections have been extensively used as the main stress-carrying members in the concrete-filled steel-grid floors. Optimum sections are used to provide approximately equal positive and negative composite-section properties. The practical design constraints are (a) to provide the least top flange width, (b) to provide a sufficient mass in the bottom flange for good bearing and welding, and (c) to provide a sufficient flange width to retain the metal form pans.

The depths of sections commonly used have been 7.6, 8.9, 10.8, and 12.7 cm (3, 3.5, 4.25, and 5 in). The spacing of the grid beams varies with the loading and span. The masses of the I-sections and their mass distributions also differ even within sections having the same depths. Auxiliary reinforcement is sometimes provided if the rolled sections are widely spaced.

Figure 1. Concrete-filled steel-grid bridge deck built in 1934 (bridge 18).

Figure 2. General surface condition of concrete-filled steel-grid bridge deck with no wearing surface after 42 years service (bridge 18).

Transverse Steel

Transverse steel is commonly provided by constructing the grid system with top and bottom cross bars.

The top cross bars have two important functions. First, they serve to armor the deck and, therefore, play an important role in reducing shrinkage cracks, which significantly increases deck durability. Second, they are a part of the transverse reinforcement of the slab and, therefore, assist in the lateral distribution of concentrated wheel loads. The major function of the bottom cross bars is in the lateral distribution of concentrated wheel loads, which requires that there be sufficient tensile reinforcement to resist flexural stresses in the transverse direction of the slab.

On the existing decks, the bottom cross bars and their spacing vary greatly. Rectangular and round bars have both been used in varying sizes. The bars have been spaced from 15 to 61 cm (6 to 24 in) center to center, with one approximately in the middle half of the span. In the earlier designs, only two bars were used for spans up to 1.83 m (6 ft) wide, but in later designs, three bars are used for spans up to 1.98 m (6.5 ft) wide. The current practice is to space the bars at 20.3-cm (8-in) center-to-center intervals, except within 30.5 cm (1 ft) of the supports.

The amount of transverse steel provided varies widely among the bridges (Table 2). The total transverse reinforcement (top and bottom) based on the gross section of the main steel varied from 15.7 to 35.22 percent. The bottom reinforcement varied from 3.10 to 21.65 percent, and the top reinforcement varied from 8.57 to 24.32 percent. These differences exist because there are no design specifications for transverse reinforcement, and engineering judgments have varied.

No problems have been reported where the total transverse steel exceeded 18 percent. The distribution of the reinforcement between the top and bottom cross bars is found to be compensatory. Good performance has been reported where the bottom reinforce-

Table 1. Existing concrete-filled steel-grid bridge decks.

Bridge No.	Bridge Name	Year Built	Owner	Grid Depth (mm)	Approximate Deck Area (m^2)
1	South 10th Street	1932	Allegheny County, PA	76.2	4 738
2	Upper Black Eddy	1933	Delaware River Joint Toll Bridge Commission	88.9	1 394
3	Highland Park	1937	Pennsylvania Department of Transportation	108.0	10 325
4	Manhattan	1938	New York City	88.9	17 211
5	CT-661 (Middletown)	1938	Connecticut Department of Transportation	88.9	5 017
6	Main Avenue	1939	Ohio Department of Transportation	108.0	35 742
7	East 21st Street	1939	Ohio Department of Transportation	108.0	6 689
8	Erie Avenue	1939	Ohio Department of Transportation	108.0	3 103
9	Bronx-Whitestone	1939	Triborough Bridge and Tunnel Authority	108.0	19 733
10	Charter Oak	1942	Connecticut Department of Transportation	108.0	3 755
11	North	1950	Pennsylvania Department of Transportation	108.0	20 506
12	Penrose	1951	Pennsylvania Department of Transportation	108.0	3 198
13	Patapsco Project	1955	Maryland Transportation Authority	108.0	35 273
14	Walt Whitman	1956	Delaware River Port Authority	127	89 915
15	Mackinac Straits	1957	Mackinac Bridge Authority	108.0	16 500
16	Throgs Neck	1961	Triborough Bridge and Tunnel Authority	127	20 547
17	Verrazano Narrows	1964	Triborough Bridge and Tunnel Authority	108.0	91 986

Note: 1 mm = 0.039 in and 1 m^2 = 10.76 ft^2.

Figure 3. Construction details of typical concrete-filled steel-grid floor.

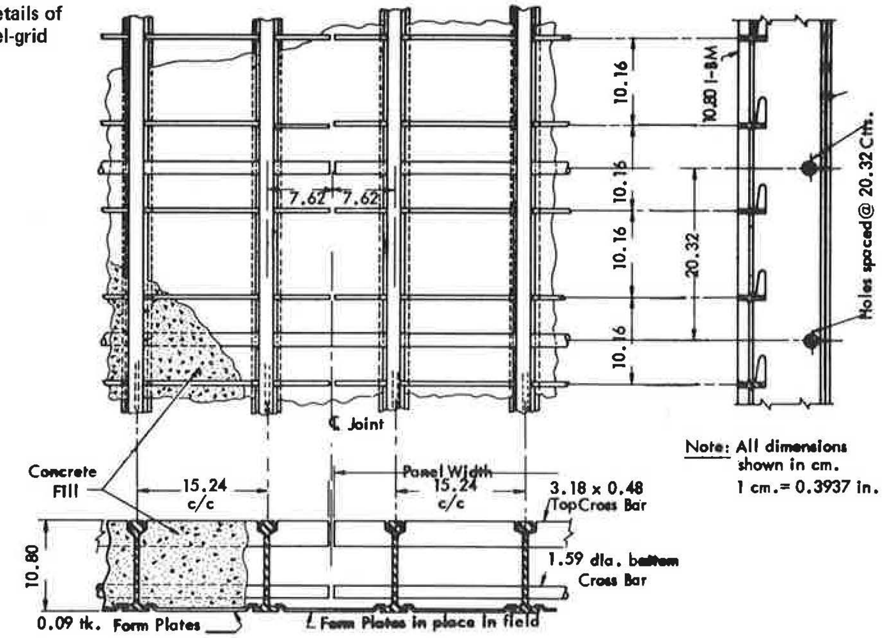

Figure 4. Welding requirements of typical concrete-filled steel-grid floor.

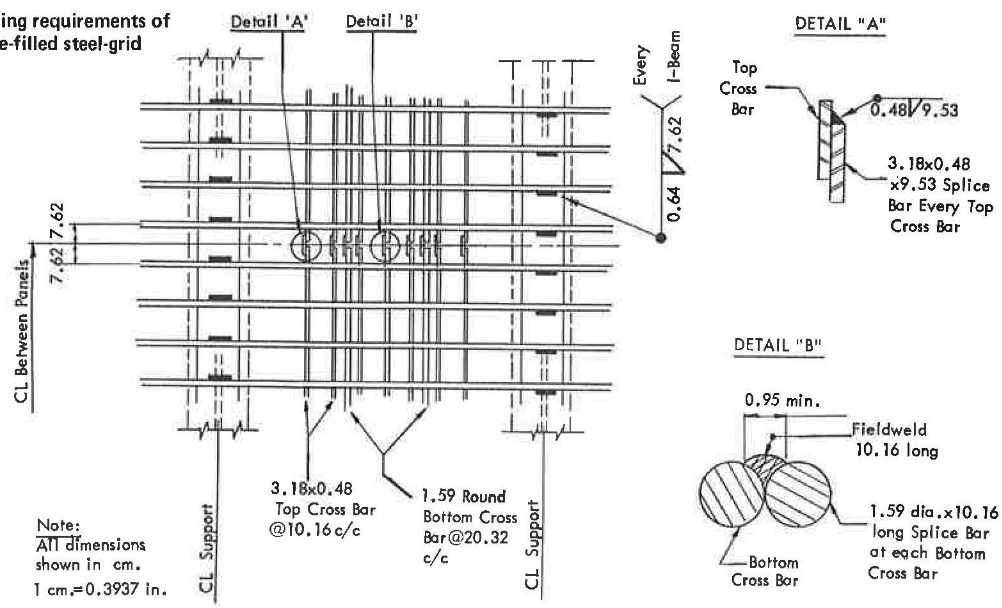

Table 2. Transverse steel and welding on existing concrete-filled steel-grid bridge decks.

Bridge No.	Transverse Steel[a] (percentage of main steel) Bottom	Top	Total	6-mm Fillet Weld[b] (%)
3	8.60	21.00	29.60	14.9
4	12.61	22.61	35.22	49.6
5	3.35	16.95	20.30	13.2
6	3.90	12.62	16.52	19.8
7	5.51	12.60	18.11	24.8
8	5.51	12.60	18.11	24.8
9	17.00	12.60	29.60	16.5
10	10.50	13.39	23.89	19.8
11	3.62	12.60	16.22	13.2
12	3.10	12.60	15.70	13.2
13	12.67	18.90	31.57	26.4[c]
14	15.84	9.64	25.48	75.6[c]
15	8.70	24.32	33.02	52.9
16	17.02	8.57	25.59	90.8[c]
17	21.65	12.37	34.02	70.5

[a] Based on gross areas.
[b] 1% fillet weld = 0.12 in/ft.
[c] Minimum welding where amount varied.

ment exceeded 5 percent of the gross area of the main members. However, when the bottom cross bars were widely spaced [61 cm (2 ft) on centers] and not adequately compensated for by the top cross bars, the deck performance has been unsatisfactory not only where there was less than 18 percent transverse reinforcement, but also where the splicing of cross bars and the welding of grid beams to the stringers was minimal.

Fastening of Grid to Supports

Both welding and bolting have been used to fasten the main beams of the grid decks to the supports. Welding has been popular and economical. Because of this positive connection, the grid floor filled with concrete has a composite action with the supporting steel. To ensure a durable and lasting connection, the weld must be designed to withstand the anticipated stresses.

The amount of welding is another area in which the details differ among the existing decks (Table 2). In the earlier designs, a 6.35-mm (0.25-in) fillet weld, which gives an average of 18.75 percent (2.25 in/ft) on the stringers, was used. This was later increased to an average of 25 percent (3 in/ft) on the stringer, and current practice is to provide an average of 50 percent (6 in/ft).

These welding specifications are the manufacturers' recommended minimums based on experience. However, design load, stringer size, spacing, and spans should also be considered in determining the size of the welds. However, on the existing concrete-filled steel-grid decks, no failures attributed to fatigue have been reported.

Splicing Adjacent Panels

Splicing of the cross bars is important to maintain continuity and avoid weak links in the slab. In the earlier designs, all the bottom cross bars were welded, but only a few top cross bars were welded. The current practice is to weld all top and all bottom cross bars. Continuity of the main beams in a grid slab has always been maintained by a welded connection, whenever required.

Table 3. Condition of concrete-filled steel-grid bridge decks.

Bridge No.	Year Built	Approximate Deck Area (m^2)	Percentage Spalled	Mean Chloride Concentration (kg/m^3)
18	1934	43	0.0	6.22
19	1940	434	0.0	2.61
20	1958	241	—	0.15
21	1932	4645	0.0	1.72
22	1932	1279	0.0	0.63
23	1937	2880	—	1.12
24	1931	3292	—	3.90
25	1940	8941	—	2.07

Note: 1 m^2 = 10.76 ft^2 and 1 kg/m^3 = 1.69 lb/yd^3

Table 4. Condition of Penn-Lincoln parkway bridges.

Bridge No.	Year Built	Approximate Deck Area (m^2)	Percentage Spalled	Mean Chloride Concentration (kg/m^3)
26	1953	3062	0.0	0.34
27	1953	4852	2.0	0.45
28	1953	3974	—	0.86
29	1953	1450	2.0	3.27
30	1958	4618	—	2.12
31	1958	4618	—	1.83
32	1958	3933	—	4.22
33	1958	6639	45.0	3.55
34	1953	2535	—	6.47
35	1956	124	50.0	2.98
36	1956	2575	25.0	5.55
37	1958	1570	5.0	3.11
38	1951	8012	12.0	4.67
39	1951	3099	70.0	2.59
40	1952	681	32.0	3.27
41	1951	744	—	3.18
42	1951	1175	—	5.64
43	1948	2111	—	5.43
44				
Older portion	1951	439	5.0	3.83
Widened right lane	1971	110	0.0	0.0
45	1950	1079	18.0	3.04
46	1950	479	2.0	4.62
47	1961	557	45.0	4.62
48	1961	3212	5.0	3.27
49	1961	4505	—	5.09
50	1962	1598	7.0	1.61
51	1962	1998	37.0	0.18
52	1962	1971	22.0	4.45
53	1962	604	5.0	0.27
54	1962	604	4.0	0.77
55	1962	1022	3.0	0.12
56	1969	3679	—	0.14

Note: 1 m^2 = 10.76 ft^2 and 1 kg/m^3 = 1.69 lb/yd^3

The details of splicing top and bottom cross bars and grid beams in adjacent panels vary, depending on the engineer's judgment; different details have been used for different bridges. The type and size of cross bars and the nature of the supports govern the splice design.

Those decks where all the top and bottom cross bars were spliced either by welding or by additional lap bars have been trouble free. Simple lap splices with 5.1-cm (2-in) long welds have been as effective as conservatively designed ones.

Concrete and Metal Form Pans

It was not possible to obtain data on the mix proportions and the quality control of the concrete used in the different bridges. But in all cases examined, the soundness of the concrete has not been affected, and spalling has not been observed.

The metal forms used have generally been 0.91 or 1.21-mm (no. 20 or no. 18) commercial-quality steel—sometimes galvanized, but mostly painted on the exposed side. These pan-shaped metal forms have not shown any signs of distress after prolonged use except at places where there is a direct water leakage and, therefore, some rusting. They have been used only to retain concrete and have never been considered to be a part of the structural slab. Some precast decks have been made without permanent metal form pans.

Wearing Surfaces

The grid decks on many of the bridges had had the concrete poured flush with the top of the grid steel. No additional wearing surface was ever applied. Such decks are still in service and, after 30 to 40 years of use, show signs of surface wear mainly in the form of cupping of the concrete enclosed within the cells formed by the main beams and the top cross bars. The depth of the cupping varies from 3.2 to 12.7 mm (0.13 to 0.5 in) below the level of the top of the steel. On some decks, the riding quality has been improved by the application of asphaltic wearing surfaces. On bridge 6, an epoxy system was used to provide a new wearing surface in 1974. On bridge 22, a 25.4-mm (1-in) thick wearing surface of latex-modified concrete was applied in 1973, after 40 years of service without any wearing of the surface. This has worked well and is in good condition.

Some of the grid decks had been constructed with the concrete poured to a depth of 19 mm (0.75 in) above the top of the grid steel. This overfill was inadequate and did not last long under traffic. However, the structural slabs remained unaffected and are still in service.

The grid deck on bridge 17 was overfilled with concrete in one pour to a depth of 44.4 mm (1.75 in) above the top of the grid steel. This has performed excellently.

CHLORIDE CONCENTRATIONS

To assess the effects of deicing salts on the deterioration of two types of bridge decks, 42 reinforced-concrete-slab bridge decks on the Penn-Lincoln Parkway in Pittsburgh and I-79 were sampled, analyzed for chloride concentrations, and evaluated for the physical distress of their riding surfaces. Eight concrete-filled steel-grid bridge decks were similarly tested.

Both the parkway and the I-79 bridges were chosen for study because of the comparative variables associated with their service life. All of each set were similarly constructed, have experienced the same traffic conditions, and, most importantly, have probably had relatively similar quantities of salt applied. However, the I-79 structures have experienced a shorter salting period than the parkway bridges because of their newer construction. Also, quality control was vastly improved during their construction period. Therefore, a study of these bridges should provide information about the effects of chlorides during an early period in the service life of a bridge deck and of whether or not their concrete, which was made with better quality control, has a greater ability to retard chloride intrusion.

All eight concrete-filled steel-grid decks sampled were in the Pennsylvania Department of Transportation's engineering district 11-0 and had service lives greater than 17 years.

Samples for chloride testing were recovered from a zone 12.7 mm (0.5 in) above the top mat of reinforcing steel for the parkway and I-79 bridges. For the concrete-filled grid decks, the samples were collected at a depth of 38.1 mm (1.5 in) below the top surface of the deck steel. The procedure developed by Berman (9) was used for the chloride analyses.

The results of the chloride tests of the concrete-filled grid decks (bridges 18 through 25) are given in Table 3. The results for the parkway bridge decks (bridges 26 through 56) and the I-79 bridge decks (bridges 57 through 67) are given in Tables 4 and 5 respectively.

The average chloride concentration of the parkway bridges is 2.95 kg/m^3 (4.98 lb/yd^3) of concrete. The decks on bridges 26 through 36 (with the exception of bridges 30, 31, and 32) were all constructed at the beginning of the bare-pavement policy and had the highest mean chloride concentration [3.49 kg/m^3 (5.88 lb/yd^3) of concrete].

Only 3 of the 18 decks in this group had chloride concentrations of less than 1.19 kg/m^3 (2 lb/yd^3) of concrete. Bridge 26, after 23 years in service, had a chloride concentration of 0.34 kg/m^3 (0.570 lb/yd^3) of concrete and showed no surface spalling. No explanation can be offered for this because there were areas of insufficient concrete cover.

Bridges 47 through 55 and bridges 30, 31, and 32 were constructed between 1958 and 1962 and had a mean chloride concentration of 2.37 kg/m^3 (4 lb/yd^3) of concrete. The surface spalls varied from 3 to 45 percent of the traffic lanes. In general, all these decks were in poor condition.

The bridge decks on I-79 were constructed between 1965 and 1973. These decks represent a more advanced period in highway construction techniques. Their mean chloride concentration is 1.0 kg/m^3 (1.68 lb/yd^3) of concrete. Twenty-seven percent of the 22 decks tested showed chloride concentrations greater than 1.19 kg/m^3 (2 lb/yd^3) of concrete. Two of these decks are only 5 years old.

In general, these 22 decks are in good condition. The largest amount of surface spalling is on bridge 57, which has 1 percent of its area spalled and a chloride concentration of 4.81 kg/m^3 (8.11 lb/yd^3) of concrete.

The mean chloride concentration of the concrete-filled grid decks was 2.30 kg/m^3 (3.88 lb/yd^3) of concrete. Although the average chloride concentrations of the parkway and the concrete-filled grid decks are similar, their surface spalling problems differ widely.

None of the steel-grid decks showed any signs of physical distress in their deck surface. On the contrary, all the parkway decks, with the exception of bridge 26, showed from moderate to severe surface spalling. The problems of the parkway decks are one of the reasons for the $130 million parkway safety update project that will eventually replace 95 percent of the reinforced-concrete slab decks of the main-line bridges.

The durability of concrete-filled steel-grid decks in a chloride-containing environment is illustrated by bridge 21 (Figure 5). This deck has been in service for 44 years and had a mean chloride concentration of 1.92 kg/m^3 (2.90 lb/yd^3) of concrete. The overall roadway surface of approximately 4645 m^2 (50 000 ft^2) is in a remarkably good condition, although rust staining is evident on the top surface of concrete.

Table 5. Condition of I-79 bridges.

Bridge No.	Year Built	Approximate Deck Area (m^2)	Percentage Spalled	Mean Chloride Concentration (kg/m^3)
57				
Northbound	1965	1731	1.0	4.81
Southbound	1965	1731	0.5	2.32
58				
Northbound	1965	4047	0.5	1.16
Southbound	1965	4047	0.5	1.33
59				
Northbound	1965	1430	0.5	0.75
Southbound	1965	1430	0.5	2.09
60				
Northbound	1965	4101	0.5	0.77
Southbound	1965	4101	0.5	0.28
61				
Northbound	1972	1534	0.0	0.31
Southbound	1972	1534	0.0	0.32
62				
Northbound	1972	5627	0.0	0.37
Southbound	1972	5627	0.0	0.28
63				
Northbound	1973	2161	0.0	0.45
Southbound	1973	2161	0.0	0.61
64				
Northbound	1973	1944	0.0	0.49
Southbound	1973	1944	0.0	0.41
65				
Northbound	1973	773	0.0	0.47
Southbound	1973	773	0.0	0.60
66				
Northbound	1971	1823	0.0	0.50
Southbound	1971	1823	0.0	0.75
67				
Northbound	1971	2065	0.5	1.70
Southbound	1971	2065	0.0	1.21

Note: 1 m^2 = 10.76 ft^2 and 1 kg/m^3 = 1.69 lb/yd^3.

Figure 5. Tenth Street Bridge, built in 1932 (bridge 21).

CONCLUSIONS

The following conclusions can be drawn from the data presented in this paper.

Research and test data on steel-grid systems have not been available. The only guide for design has been the AASHO specifications. The designs have varied in details, and these have affected their performance. The unsatisfactory performance of two bridge decks has been traced to inadequate welding of grids to supports, provision of transverse steel, and splicing of adjacent grid panels. These details can be improved by proper research and analysis.

The chloride concentrations found in concrete-filled steel-grid bridge decks are sufficient to initiate corrosion of the steel. However, none of the grid decks tested showed any surface spalling.

The chloride concentrations found in the reinforced-concrete slab decks of the parkway bridges are sufficient to initiate corrosion of the reinforcing steel. The physical condition of the majority of these bridge decks shows that surface spalling is a serious problem.

The chloride concentrations found in the reinforced-concrete slab decks of the bridges on I-79 showed that 27 percent of the decks sampled contained chlorides in amounts sufficient to initiate corrosion of the reinforcing steel. However, since the oldest deck is only 11 years old and all the decks are in generally good condition, these bridge decks are merely undergoing the preliminary phases of steel corrosion, and surface spalls have not had sufficient time to develop.

The single most important conclusion of this study is that concrete-filled steel-grid bridge decks are effective in providing long serviceability in chloride-containing environments. This is accomplished without the help of waterproofing membranes, coatings on steel, cathodic protection, or any other substances designed to prolong bridge deck life. At the same time, the construction of such decks does not require high-caliber quality control.

A review of two bridge biddings in October 1975, indicates that concrete-filled steel-grid decks are economically competitive with reinforced-concrete slab decks. The bid price received for the reinforced-concrete slab decks in the parkway west safety update project [13 350 m^2 (143 560 ft^2) on four bridges] was \$125.60/m^2 (\$11.63/ft^2), including galvanized bars and a waterproofing membrane. The low bid received for the replacement of one 434-m^2 (4669-ft^2) bridge deck was \$139.60/m^2 (\$12.00/ft^2) for a concrete-filled steel-grid deck. Thus, the concrete-filled steel-grid bridge deck may be an economical, lightweight, and durable solution to the problem of bridge-deck deterioration.

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Possible Explanation of Concrete Pop-Outs

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Several years of research relating to damage to concrete and aggregates undergoing freezing and thawing is summarized. Basic principles involving freezing and the attendant pressures are discussed. These principles were applied to the evaluation of concrete in experiments on concretes having low and high air contents. The freeze-thaw characteristics of saturated aggregates relative to their physical properties such as porosity, absorption, and bulk specific gravity were studied by submerging individual particles in prechilled mercury. The pressures associated with pop-outs in concrete were monitored and are discussed in theoretical terms.

Voids occur in concrete through the entrapment and entrainment of air, the occlusion of excess mix water, differences in the specific volumes of reactants and hydration products, leaching of hydration products such as CaO and the use of porous aggregates. Those voids that are easily saturated affect the durability of the concrete unfavorably while those that are less permeable increase the durability. Much water is occluded in concrete in the form of excess mix water and water ab-