Deterioration of Structural Concrete in Indiana

D. W. Lewis

Research Engineer
Joint Highway Research Project
Purdue University

INTRODUCTION

This paper presents the results of a general performance survey of overhead structures and bridges in Indiana. The purpose of the survey was to determine the extent of deterioration of structural concrete, and if possible, the probable causes of such deterioration.

The survey was of a reconnaissance nature, limited to such inspection as could be made from, on and under the structures without the use of any special equipment. Specifically, the survey was intended to:

(a) Furnish information with respect to the general extent and importance of concrete deterioration in structures,
(b) Determine the types of deterioration that exist and their location in the structures, and
(c) Determine the probable or possible causes of the defects found to exist.

In addition, structural defects and failures from loads were noted for those structures in which they existed.

SCOPE

Number of Structures

A list of six or seven structures in each district was prepared by the Bridge Department, State Highway Department of Indiana, to serve as a starting point in the survey. To this basic list were added other structures recommended for inspection by the district offices, and some chosen at random that could be conveniently included in the survey.

A total of 125 structures, varying in date built from 1909 to 1949 were inspected. Several types of structures were included. Table 1 shows the number of structures of each type inspected in each district.
### TABLE 1.
Types of Structures Inspected in Each District

<table>
<thead>
<tr>
<th>District</th>
<th>Reinforced Concrete Girders</th>
<th>Reinforced Concrete Arches</th>
<th>Steel Girders and Trusses</th>
<th>Underpasses</th>
<th>Reinforced Concrete Slabs</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crawfordsville</td>
<td>7</td>
<td>7</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Fort Wayne</td>
<td>8</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>0</td>
<td>21</td>
</tr>
<tr>
<td>Greenfield</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>LaPorte</td>
<td>12</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Seymour</td>
<td>10</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>23</td>
</tr>
<tr>
<td>Vincennes</td>
<td>7</td>
<td>3</td>
<td>8</td>
<td>0</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>53</strong></td>
<td><strong>19</strong></td>
<td><strong>23</strong></td>
<td><strong>7</strong></td>
<td><strong>4</strong></td>
<td><strong>125</strong></td>
</tr>
</tbody>
</table>

Structures are classified in the table according to the type of design used in the greatest number of spans in those cases where more than one type was used in a single structure. It will be noted that a large part of the total structures inspected were reinforced concrete girders. In addition, an equal number of the structures, 53, were overheads. Of the 53 overheads, there were 37 reinforced concrete girders, 11 steel beams, 3 girders or trusses, 1 arch and 1 slab structure.

**Defects**

Concrete deterioration found was classified in three categories as follows:

(a) *Scaling*. This deterioration is characterized by separation and loss of surface layers or fragments of concrete from roadways, curbs, and sidewalks. The most common cause of scaling is the action of ice removal chemicals.

(b) *D-lines*. The so-called “D-lines” or “Deterioration-lines” are small cracks, usually rather closely spaced, and filled with deposits of calcium carbonate. They form a fairly parallel pattern and tend to develop first along the edges of a concrete slab or structural member. The most common cause of D-lines is damage from freezing and thawing.

(c) *Mapcracking*. The cracks referred to as “mapcracking” form in a random pattern, lacking the parallelism of D-lines. The cracks are ordinarily open, containing no deposited material and are usually more widely separated than D-lines. Differential volume changes between the interior and exterior concrete are responsible for mapcracking. Such volume changes are most frequently caused by cement-aggregate reactions that produce internal expansion.
In addition to the concrete deterioration discussed above, structural defects were recorded whenever found. These fell into two general categories, (a) actual cracks or breaks of a structural nature, and (b) conditions that might, if uncorrected, result in structural failure of some sort in the future.

CONCRETE DETERIORATION

Scaling

The type of concrete deterioration most frequently encountered was scaling of the decks, curbs and sidewalks of the structures inspected. It was found in all types of structures. The use of salts for ice removal was probably the major factor in causing the scaling. Most of the structures inspected were built prior to the use of air-entrained concrete in the decks for prevention of scaling.

Many of the structures had bituminous resurfaces on the decks, either because of previous scaling and deterioration, or as part of highway resurfacing projects including both the roads and structures. A total of 70 structures were inspected that still had a concrete deck surface. Of these, 50 were scaled to a moderate or severe degree, and many others were beginning to show a slight amount of surface scaling.

By highway districts, the structures showing a considerable amount of scaling were as follows:

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of Structures Scaled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crawfordsville</td>
<td>13 of 14 structures scaled,</td>
</tr>
<tr>
<td>Fort Wayne</td>
<td>10 of 11 structures scaled,</td>
</tr>
<tr>
<td>Greenfield</td>
<td>7 of 13 structures scaled,</td>
</tr>
<tr>
<td>LaPorte</td>
<td>11 of 13 structures scaled,</td>
</tr>
<tr>
<td>Seymour</td>
<td>4 of 6 structures scaled,</td>
</tr>
<tr>
<td>Vincennes</td>
<td>5 of 13 structures scaled,</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>50 70</strong></td>
</tr>
</tbody>
</table>

Scaling tended to be concentrated near the curbs and along transverse cracks. This tendency was found throughout all types of structures. Apparently the vehicles splash the salt solution out of the heavily traveled lanes, and it collects along cracks and joints, in the gutters, and on the curbs and sidewalks. In many structures the severity of scaling changed radically at construction joints, illustrating the effects of construction practices on deterioration. The differences in durability in different portions of the deck are believed to be caused by variations
in the amounts of water in the concrete mixes—excessive water causing lower resistance to scaling.

Fig. 1 illustrates extremely severe scaling, extending to a depth of $1\frac{1}{2}$ to 2 inches in places. In many cases, deteriorated areas were found on the bottoms of the decks directly below the most severely scaled areas. This would indicate that severe scaling results in further ponding of water and salt. The ultimate effect is saturation of the concrete and destruction of the deck by freezing and thawing.

On some structures efforts have been made to patch badly scaled decks with bituminous mixes. These efforts have not, in general, been very successful. The patches may increase the surface roughness, further ponding the salt and water. Scaling continues between the patched areas and under the edges of them. Water can still penetrate and saturate the concrete. It seems probable that complete resurfacing of the deck is the only effective measure to employ.

The northern districts appear to have a higher percentage of scaled structures than do those in the southern part of the state. In addition, the scaling that does occur is believed to be more severe, in general, in the northern part.
Fig. 2. Deteriorated diaphragms, girders and bent cap, Structure 41-Q-699, Crawfordsville District.

D-lines and Mapcracking

Reinforced Concrete Girders

D-lines formed in the stiffening diaphragms over intermediate piers and bends, in the mudwalls at end abutments, and in the adjacent girders, bent caps and deck slabs were common in reinforced concrete girder structures. A total of 53 such structures were inspected, including 37 overheads and 16 bridges. Of these 44 showed definite evidences of such deterioration, only nine did not. Six of the nine that had no such deterioration were in the two southernmost highway districts where 17 of the structures were located.

Fig. 2 shows typical deterioration of this type, affecting the diaphragms, bent cap and the ends of the girders. There were many more severe cases, with the cap affected from top to bottom and the underside of the deck slab D-lined. The ends of the bent caps in some structures were falling apart; bituminous material had been painted on them in an effort to provide some protection.

This deterioration is apparently caused by the leakage of water and ice removal salts into the deck joints. Since the diaphragms extend to the top of the bent cap, the joint acts as a reservoir to retain the
Fig. 3. Diaphragm and girder deterioration, Structure 43-J-1035, Crawfordsville District.

water until it soaks into the concrete. In several structures, stalactites had formed under the caps and were dripping water slowly although there had been no rain for weeks. The deteriorated concrete is probably highly saturated most of the time.

The deterioration usually begins in the diaphragms and then spreads into the adjacent concrete, although there are cases where the bent caps have been affected first. In the regular reinforced concrete girders, the D-lines are more severe at intermediate bents than at the ends. This may be due to a greater thickness of concrete in the end mudwalls than in intermediate diaphragms, and also to the fact that the end joints can drain over the back of the cap into the fill. In places where concrete girder and steel beam spans are combined, the deterioration is usually minor at bents at the junction of the two types, where only one diaphragm extends to the cap.

Three reinforced girder bridges on U. S. 41 south of Evansville provide evidence of the effect of draining the joints. Holes were left open through the diaphragms in these structures, thus draining the joints. No deterioration of the diaphragms, ends of girders, etc. existed in these bridges. Instead, all visible deterioration was confined to the
ends of the caps (outside of the girders) and to the mudwalls at the ends.

Figs. 3 and 4 show two conditions encountered in Structure 43-J-1035 in the Crawfordsville District. Fig. 3 shows the conditions at a bent where some leakage has occurred at the end of the joint. Some corrosion of the end of the cap has taken place and D-lines are evident in the diaphragms and ends of the girders. In Fig. 4 another bent is illustrated at which leakage from the joint has caused extensive deterioration of the end of the cap. Diaphragms, girders and the cap under the structure are in good condition, indicating that the drainage of the joint was quite efficient. Condition of the cap end, however, would indicate that joint drainage over the cap itself may not be a desirable solution to the problem.

It would appear that reinforced concrete girder bridges have somewhat less deterioration than do overheads. This may be due, in part at least, to their flatter grade which probably makes less application of ice removal chemicals necessary. In some of the older reinforced concrete bridges, however, rather advanced deterioration may be found.
Reinforced Concrete Arches

The reinforced concrete arches inspected tended to have deterioration in certain specific locations. Nineteen arches were inspected; all but three were of the filled spandrel type. Twelve of the arches had a considerable amount of deterioration in the railings, 15 in the spandrels, and in only four did the deterioration extend into the piers and abutments. In all of the deteriorated structures, except one, D-lines were the major evidence of damage. The other arch was seriously mapcracked.

Fig. 5 shows the extreme D-line cracking in the spandrel wall and railing on one of the early state-built arches in the Vincennes District. In this structure, all drains had been completely silted over by the stream, thus trapping water within the spandrel walls. Continuous leakage has formed stalactites along the bottom of the wall. In this case, the deterioration had spread into the pier caps at the ends and into the wing walls of the end abutments. However, very little damage appeared to have occurred in either the center portions of the piers or the arch rings.

Severe mapcracking in the railings of a structure in the Seymour District is shown in Fig. 6. In addition to the railing deterioration
shown, a large pattern of cracking (one to two feet across) is evident at many places in spandrel walls and wingwalls. The coarse aggregate in the concrete has discolored rims, indicating a chemical reaction with the cement. The excessive expansion shown by closed railing joints with many crushing and shearing failures at the joints, together with the crack pattern and discolored edges on the aggregate particles indicate a cement-aggregate reaction to be the cause.

Except for this one structure, the major cause of the deterioration found in arches is apparently freezing and thawing. Lack of drainage of water that permeates the fill is an important factor. In many cases where deterioration is just beginning, it is starting at leaking joints and cracks that are providing partial drainage. Water trapped in the fill would tend to saturate the spandrel walls, and might even be drawn into the railings to some extent by capillarity. The greater durability of the arch ring may be due to the increased resistance of the thicker section to saturation and damage, to its protected position which may result in fewer alternations of freezing and thawing, and to waterproofing of the interior surfaces at the time of construction.
Steel Beam Structures

A total of 19 steel beam structures were inspected, 11 overheads and 8 bridges. Other than scaling on the decks, D-lines from freezing and thawing were the only evidence of concrete deterioration found.

Except for the use of steel beams instead of concrete girders and the absence of stiffening diaphragms over the caps, these structures are quite similar to the reinforced concrete girder structures. They are, however, quite different in the amount of deterioration found. Of the 19 inspected, six had some railing deterioration, seven had D-lined areas on the bottom of the deck beneath badly scaled areas, only three had any deterioration in bent caps and two had D-lined mudwalls.

The apparent better durability of steel beam structures as compared to the reinforced concrete girders is believed to be primarily due to two factors:

(a) No diaphragms extend down to the tops of the bent caps to trap water and ice removal chemicals, and

(b) Extensive use of continuous beams results in fewer joints that may leak water onto the bent caps.
Several of the structures listed as "Reinforced Concrete Girders" contained some steel beam spans. As previously mentioned, bent caps at the junction of steel beam and concrete spans were generally in better condition than those supporting two concrete spans. Thus, it is generally true that, even in the same structure, the design without diaphragms extending all the way from deck to cap was the more durable. Elimination of the "water trap" or "reservoir" over the bent caps greatly decreases the deterioration.

**Steel Trusses and Girders**

The survey included a total of 23 girder and truss structures. Only scaling and D-line deterioration were encountered in them, with very few seriously damaged by concrete deterioration alone. Except for two structures that had seriously deteriorated decks, the D-lines were confined principally to the ends of bridge seats and pier caps and to areas along the tops or along structural cracks in wingwalls.

A deck failure in a small bridge in the Vincennes District is shown in Fig. 7. One-half of the deck, reported to have been made with a high alumina cement, was affected. The other half, in which a
normal portland cement is supposed to have been used, was in relatively good condition. Repairs to this structure, at least at the time of inspection, had consisted of placing small timbers across the bottom flanges of the I-beam stringers and covering them with a bituminous patch.

In some cases it appeared that differences in the construction techniques affected the durability of portions of these structures. For example, a deteriorated cap at one end of the bridge seat was the only concrete deterioration found in one large structure (other than deck scaling). An identical cap at the other end of the bridge seat was in perfect condition. Use of concrete with an excessive amount of water in the one probably accelerated its deterioration.

In other structures, such as that illustrated in Fig. 8, the deterioration was consistent. Here, the outer ends of both bridge seats were severely D-lined. However, no deterioration was found on the bridge seats under the structure.

In practically all cases of deterioration of the bridge seats and piers, the damage was confined to the ends, outside the truss itself. At these locations are found flat, horizontal surfaces onto which water and ice removal salts may be splashed by traffic and then ultimately saturate the concrete. Many of them are also exposed to the sun during the day, which may increase the number of freezing and thawing cycles as compared to other parts of the same pier or abutment.

Underpasses

A total of seven underpasses were inspected. Due to differences in design, exposure and materials, no definite trends with respect to deterioration were found. However, several of these structures did illustrate specific results of some practices in design and construction.

For example, the D-line cracking was severe around railing posts on the ballast retaining walls of an underpass in the Crawfordsville District. Sides of the walls directly under each post were also in bad condition. There was no deterioration anywhere else in the structure. The method of placing the steel posts in holes cast in the concrete obviously permitted water to enter, thus leading to the localized, but progressively spreading deterioration.

In a steel plate girder underpass in the Seymour District D-lines appeared on flat pier tops and along structural cracks, both conditions which facilitated the entry of water into the concrete. Wherever exposure conditions were similar to those that produced deterioration in other types of structures, concrete deterioration was found in the underpasses inspected.
Reinforced Concrete Slabs

Only four reinforced concrete slabs were inspected, two of them built since 1940. These two had a negligible amount of deterioration, but one was damaged considerably by structural movement.

Of the other two, only one showed any significant amount of deterioration. This was a slab overpass in the Seymour District, Structure 50-H-1348. The sidewalks, curbs and railings were D-lined and mapcracked, and a general pattern of mapcracking existed throughout the remainder of the structure. The deterioration noted appeared to be due to three causes: scaling, freezing and thawing, and cement aggregate reaction.

Structural Defects

Skew Movement

One of the most common sources of structural damage is the tendency of skewed spans to rotate. In some reinforced concrete girder overheads practically all the railing posts have been broken and curbs are also commonly broken. Notching the girders into the bent caps seems to be effective in decreasing this tendency, although some breakage of posts and spalling of the corners of the notches have been observed in these structures.

Skew movement may be found in all types of structures, and may in some cases be responsible for damage discussed here under other headings—such as the splitting of caps and seats at shoe bolts.

Fig. 9 shows the results of skew movement in a three span continuous slab bridge. Apparently all movement was at one end, resulting in a displacement of four inches. The railing was broken, and the tops torn from both wingwalls at this end.

Tilting of Abutments

Many structures show evidences of an inward tilting of abutments. This frequently results in frozen expansion joints such as that shown in Fig. 10. In this case, subsequent contraction of the continuous steel beam structure pulled the fixed side of the joint along with the deck slab, breaking the top of the mudwall and making extensive repairs necessary.

In some cases the effect of such tilting of the abutments has moved spans several inches. For example, in Structure 31-D-3558A in the Seymour District, reinforced concrete girder spans have moved six inches into the expansion end of a truss span, crushing the concrete at the girder ends and completely preventing any expansion in the truss.
Expansion rockers on most of the structures inspected were rotated far over in the expansion position, even in the wintertime. This would indicate that abutment tilting is the rule rather than the exception.

**Deck Slab Breakage**

Many of the older steel truss structures have the ends of the deck slab broken, especially at the abutment ends. The slab breaks between the end floor beam and mudwall, leaving a gap several inches wide across the roadway. Breakage of the mudwall is frequently associated with the deck slab breakage. The tilting of the abutments previously mentioned may contribute to this type of failure. Several structures were observed in which “patching” of this type of failure consisted of piling old railroad ties on the bridge seat up to deck level and then covering it with a bituminous patch.

**Cracking of Bridge Seats and Caps at Shoe Bolts**

Quite a large number of structures were observed in which the bridge seats or caps were cracked directly in line with the bolts holding
the bridge shoes in place. A number of factors may be responsible for this defect. Among these are corrosion of the shoes and bolts (some have not been painted in 20 years), skew movement, abutment tilting, and excessive contraction of the span.

The only structure inspected that was in severe distress from this defect was Structure 37-N-2083A in the Greenfield District. It is a steel girder overhead, 106' span and 71° Right Skew. Both corners of the bridge seat at the south end were cracked, that at the southeast corner had been sheared off exposing the bottom of the shoe.

**Erosion**

Unchecked erosion around a number of structures is threatening the stability of abutments and approach slabs. Although it is an easily corrected problem, it seems to be generally neglected.

Erosion around the end (spill through) bents of reinforced concrete girder overheads has, in several cases, exposed the bottoms of the bent caps. Continued erosion will result in the loss of fill under the approach slabs, with subsequent breakage and extensive repairs.
The deterioration of structural concrete is widespread in Indiana and is quite severe in many cases. It occurs with a great variety of materials, and in only a few cases can the deterioration be attributed to the materials themselves. Scaling of the decks affects all types of structures but is perhaps more severe in the overheads, most of which are built with a rather steep grade that probably necessitates the use of larger amounts of salts for ice removal. Deterioration of the deck slab from D-lines is also found in all types of structures.

The D-line deterioration from freezing and thawing is found in definite parts of the various types of structures. Thus the reinforced concrete girders are particularly susceptible to deterioration around the joints where water is trapped over the bent caps. Filled spandrel arches deteriorate in the spandrel walls from lack of drainage. Other structures have the greatest deterioration on flat surfaces on which water may collect and along leaking structural cracks or joints.

Only two structures showed any significant evidence of cement-aggregate reaction; both of these were in the Seymour District. The widespread occurrence of the deterioration, the variety of materials with which it occurs, and the tendency for it to be localized at points of extremely severe exposure indicates that the materials are not basically the cause. The rate of deterioration may be dependent upon such things as aggregate durability, and air entrainment would improve the durability in many cases. However, it is doubtful that even air entrained concrete made with carefully selected materials could consistently withstand the extremely severe exposure encountered in many of the structures.

It seems evident that the problem of preventing or minimizing the deterioration of structural concrete is primarily a problem of improving the design, construction and maintenance. Designs could be changed to eliminate some of the poorly drained portions of the structures, greater care could be taken in construction to insure the most durable and water-tight concrete possible.

In the field of maintenance, not only is better maintenance needed, but a great need exists for more "preventive maintenance". The patching of severely scaled areas on bridge decks after deterioration is far advanced is probably a case of "too little and too late". Dangerous erosion around structures is given little attention, and much of the maintenance of structural defects is inadequate.

In many cases repairs have been attempted, apparently with insufficient knowledge of what should be done or how to do it. For
example, an attempt was made to correct the joint shown in Fig. 10, but only one side was cut off. Proper maintenance originally would have avoided the subsequent mudwall breakage and the need for expensive repairs.

Repair of structures is believed to be a sufficiently specialized problem to justify the employment of specially trained crews for the work. It should be under the direction of a competent bridge engineer, and the members of the crew should have no other duties. The maintenance needs are believed to be sufficient to keep a crew busy for years in each of the districts. Such maintenance would pay large dividends through increased life of structures and through avoidance of major repairs resulting from neglect of smaller defects.

CONCLUSIONS

The general conclusions reached as a result of the performance survey reported here are:

1. Concrete deterioration is common and widespread in Indiana, but appears to be more severe in the northern part of the state.
2. In only a few cases can the concrete materials be considered primarily responsible for the deterioration.
3. Scaling and subsequent deterioration of the deck is the most common durability defect. It can be attributed primarily to the action of ice removal chemicals.
4. General freezing and thawing damage resulting in “D-lines” is very prevalent, occurring as a result of inadequate drainage in various parts of the structures.
5. Preventing or minimizing such deterioration can best be achieved by improvements in design, construction and maintenance.

RECOMMENDATIONS

Specific recommendations for improvements in design, construction and maintenance to minimize the deterioration of concrete in structures and to generally prolong their period of usefulness are:

A. Design

1. Use air entrained concrete in all parts of all structures. As high an air content as feasible should be used. (Air entrainment is currently being used in all above ground portions of Indiana’s highway structures and has been used in the decks since 1946.)
2. Eliminate all joints possible and provide drainage for those that must be used. Rigid frame and continuous span designs would help in eliminating joints.
3. Avoid the use of horizontal surfaces as much as possible.
4. Eliminate decorative copings. They form a place for deterioration to begin.
5. Use drip beads to prevent water from running under the edges of structural members.
6. Do not design "water traps" or "reservoirs" into structures. Extending diaphragms to the bent caps is an example of a design feature that should be avoided.
7. The use of some type of waterproofing on surfaces exposed to severe conditions should be considered.

B. Construction. Great care should be taken in construction to insure that:
1. All concrete contains the proper amount of air (agents should be added at the mixer if necessary to achieve this),
2. As little water as possible is used in the mix to obtain the best concrete possible, and
3. The concrete is properly placed to avoid segregation, laitance, excessive porosity or honeycombing.

C. Maintenance. A special maintenance crew should be set up in each district, under a competent bridge engineer. The following items might be included in work they would undertake:
1. Completely resurface the decks of structures that have begun to scale and deteriorate.
2. Remove the bottoms of diaphragms in reinforced concrete girders that are deteriorating, to provide drainage. Bent caps might be waterproofed at the same time.
3. Keep deck joints as well sealed as possible to prevent infiltration of water. This should also apply to resurfaced structures.
4. Repair structural damage as promptly as possible to prevent further damage or deterioration resulting from the increase in accessibility of the concrete to water.
5. Control erosion by properly channeling water around the structures.

The recommendations under "Maintenance" above are necessary if maximum life and minimum cost are to be obtained with the structures already in existence, while those for "Design" and "Construction" may help in obtaining better structures in the future. In view of the great investment in present structures, the value of proper maintenance to obtain maximum life from them is obvious. The use of special crews for this work is believed to be essential for its success in reducing the high maintenance and replacement cost of neglected structures.