Bridge Failures—
Aftermath and Investigation

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Figure 1. Cracked bents in Dan Ryan Rapid Transit, Chicago (arrows point to location of fractures). (photograph courtesy of Chicago Department of Public Works)

While riding on a train passing under the 8-year-old Dan Ryan Rapid Transit in Chicago on January 4, 1978, Herman Solarte observed a crack extending almost completely through a steel bent that was supporting the overhead superstructure. Solarte, a structural engineer, recognized the danger and notified the Chicago Transit Authority as soon as the train arrived in downtown Chicago. The Authority responded immediately; an on-site investigation revealed the major crack reported by Solarte and also major cracks in two adjacent bents. (Views of the cracked steel bents are shown in Figures 1 and 2.) For the next 11 days the city suffered a crisis of significant proportion while the major commuting line was closed to permit an investigation of the extent of the damage. Shoring was installed under the fractured bents and others before the system was reopened.

On August 28, 1982, there was a failure in a "blocked" expansion joint in the segmental post-tensioned Zilwaukee Bridge at Saginaw, Michigan. The end of the cantilever (shown in Figure 3) twisted and deflected about 5 ft, and the joint in the adjacent span rose about 3 ft. Concrete on the compression side of the blocked joint was crushed, as shown in Figure 4. Construction of the bridge was delayed for several months as investigators sought the cause of failure and developed repair procedures for the extensive damage.

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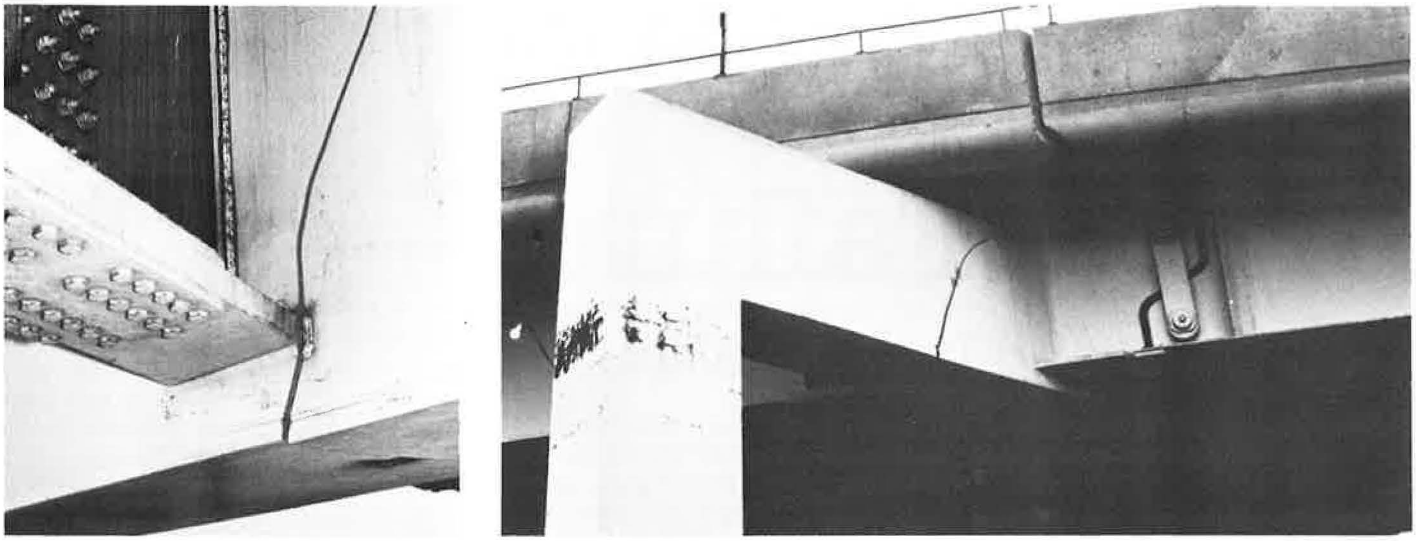

Figure 2. View of cracks in bents in Dan Ryan Rapid Transit, Chicago: (*left*) side of bent No. 24; (*right*) side of bent No. 25. (photograph courtesy of Chicago Department of Public Works)

Similar unfortunate events have occurred elsewhere in recent years. Bridge engineers will not forget the collapse of the 39-year-old Point Pleasant Bridge over the Ohio River on December 15, 1967, in which 46 lives were lost.

On May 7, 1975, the 7-year-old Lafayette Street Bridge over the Mississippi River in St. Paul, Minnesota, was closed following the discovery of a major crack in one of the two main steel girders in this three-span continuous structure.

A nearly new Interstate 79 Bridge crossing the Ohio River near Pittsburgh was closed for over 2 months following the discovery on January 28, 1977, of a fracture in an electro-slag welded shop splice in the bottom flange of a 350-ft center span of a three-span continuous girder.

On May 10, 1979, cracking and distress were observed in a joint of the segmental post-tensioned concrete Kishwaukee Bridge in Illinois. Opening of the nearly completed structure was delayed for almost a year.

The 5-year-old Marquette-Joliet Memorial Bridge over the Mississippi River at Prairie du Chien was closed on January 16, 1981, for 7 months following the discovery of cracking of the tie girders in the arch structure.

Construction of Ramp C of the Cline Avenue Extension Expressway in East Chicago, Indiana, a post-tensioned, cast-in-place concrete box girder bridge, was delayed following the collapse of the supporting scaffolding on April 15, 1982. Twelve people died in the accident.

The 1-year-old Veterans Memorial Bridge over the Missouri River at Sioux City was closed in June 1982, for about 6 months after a fracture was found to have completely severed the top flange of one of the tie girders in this 425-ft-span arch bridge.

Recently, the heavily traveled 25-year-old Mianus River Bridge in Connecticut was closed for several weeks after the collapse of a section of the bridge on June 28, 1983. Three lives were lost in this accident, which is still under investigation.

Two important observations are apparent from this brief review of recent failures. First, even bridges that might be considered nonredundant are often surprisingly capable of adjusting to the loss of a major member or piece and of remaining in service for a significant period of time before the failure is discovered. The capability to recognize and evaluate these alternate load paths is necessary in the review and assessment of existing bridges.

Second, all of the cited failures that occurred during construction involved concrete structures, whereas the failures that occurred in service involved steel structures; clearly, this is indicative of an underlying problem with design and construction practices that needs attention by bridge engineers.

The purpose of this article is to provide some guidance for those who must take the lead in the aftermath of a major failure. Whereas each failure is unique, the technical considerations that come to the forefront during the course of the ensuing investigation are often similar.

AFTERMATH

The failure, subsequent evaluation, and rapid reopening of the Dan Ryan Rapid Transit provides an example of the actions necessary in the aftermath of a major bridge failure. The Chicago Transit Authority and the Chicago Department of Public Works jointly recognized that every possible effort had to be expended toward the reopening of the system. A Technical Committee was immediately established, which included representatives of the

Transit Authority and the Department of Public Works and their consultants, as well as the designer and fabricator of the steel superstructure. The Technical Committee met daily at the site of the collapse during the early critical stages, usually in a bus, receiving reports of various investigative teams, arriving at collective judgments as to the extent of the work required before the system could be reopened, and coordinating the efforts of the involved parties in order to get the system back in operation as rapidly as possible.

It is evident from this example that the actions taken shortly after a major failure often have a significant impact on the speed with which the facility can be placed back in operation. The immediate consideration, of course, is the rescue of people caught in the collapse and the safety of people working in the area. Security may also be important, especially if the failure is of a nature that attracts the public to the site.

Handling of the demands of the media for information about the failure may need to be considered. These demands may be intense after the failure and during the period of time the system is closed. Certainly the public has a right to information that affects the use of vital transportation systems. Nevertheless, because of potential liability, the involved parties may be driven into defensive positions that work to the detriment of the reopening of the system. These situations appear to work out the best when the owner takes a strong lead and invites the cooperation of all of the involved parties.

The next consideration relates to the amount of time available for site investigation before the damaged or collapsed portions of the structure are removed or discarded. It is essential to recognize that allowing investigators ample opportunity to examine the structure before it is disturbed may be important in determining the cause of the problem. However, the actions of the investigators may need to be monitored, as each investigator may have an interest in obtaining samples of materials or pieces involved in the failure. In addition, protecting such key components as the fresh steel fracture surfaces should receive immediate attention. Oxidation occurs quickly, especially in damp environments. Protection of fracture surfaces will enhance the subsequent opportunities for metallurgical examination. Also, time must be taken to develop a plan for obtaining samples of the steel for subsequent laboratory testing.

The final consideration concerns the repair of the system and restoration of service. Although it is important to establish conservative assumptions in carrying out the repair of any damage, overreaction carried to the point of unnecessary reconstruction may unduly delay the process.

A qualified consultant may be of considerable help to an owner or to the involved parties during the aftermath of a failure. An important requirement is the previous experience of the consultant with similar situations, because knowledgeable advice must be available when decisions need to be made rapidly. The technical competence of the consultant in the area related to the investigation is also important, because the parties will more readily accept the views of a person with recognized expertise.

INVESTIGATION

An investigation of a bridge failure generally includes: (a) a survey and documentation of conditions at the time of the collapse; (b) procurement, examination, and testing of failed components and representative materials; (c) an analysis of the structure, preferably beyond that of a review of the original design; and (d) a review of the history of the bridge, beginning with its design and construction.

Documentation of Conditions

Investigators rely heavily on photographs to document the conditions at the site of a failure. Working with a camera, tape recorder or field notebook, and pocket scale, an investigator or investigative team is usually able to cover the scene of a failure in considerable detail. A variety of equipment is available that may be useful in making detailed measurements. Often, aerial or overhead photographs, taken before pieces are disturbed and then later during removal of the debris, are useful. Video

Figure 3. Deflected cantilever in Zilwaukee Bridge, Saginaw, Michigan. (photograph courtesy of Michigan Department of Transportation)

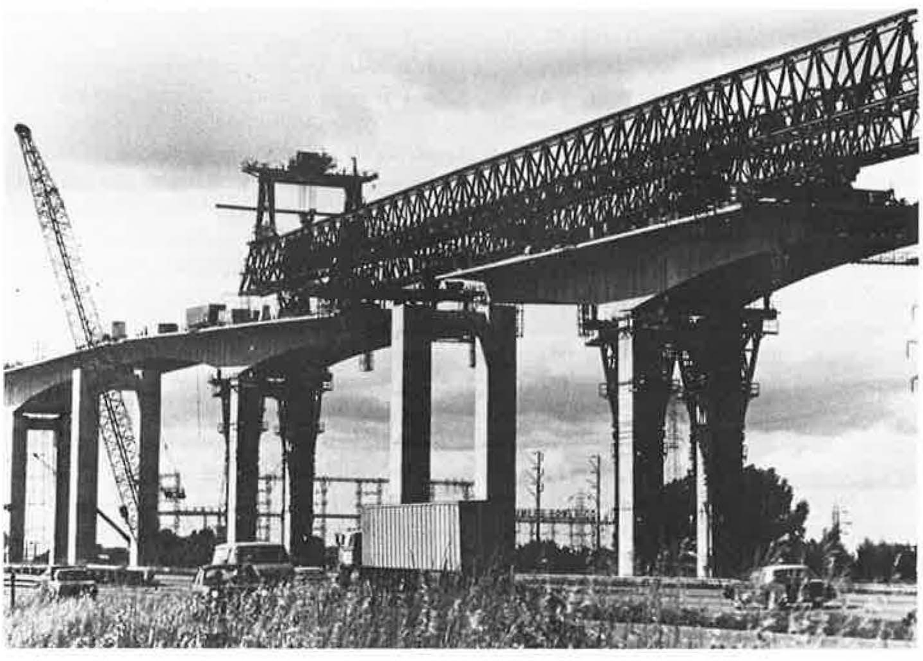

Figure 4. Spalled compressive region of "blocked" joint in Zilwaukee Bridge. (photograph courtesy of Michigan Department of Transportation)

tapes of an area may also provide a useful record, although it is often difficult to achieve good resolution.

A reference system must be established for the observations. If drawings of the structure can be obtained, it is almost always preferable to use the original grid system.

In observing the conditions at the site, it is important to look beyond the immediate area of the failure. Conditions such as blocked expansion joints or missing elements may have had a significant influence on the distribution of forces within the structure at the time of the failure. For example, when the fractures occurred in the Dan Ryan Rapid Transit bents, there were numerous investigators and workers at the site. Yet it was several days before it was noticed that there was a missing pin and displaced link in one of the four girders framing into the fractured bent. Perhaps because of that delay, the pin was never located. Although it was concluded that the missing pin had little influence on the condition that caused the failure, the recovery of that pin would have cleared up several questions that were never resolved in the investigation.

During the work at the site, the investigators should closely examine all of the other elements in the bridge that are similar to the element believed to have precipitated the failure. The limitations of ultrasonic and radiographic testing of steel bridge members should be recognized, particularly when the members are in hard-to-reach locations. In general, examination by light grinding and dye penetrant or magnetic particle will often be far superior for detecting cracks in other, similar elements of the structure.

Procurement, Examination, and Testing

In virtually every failure, the properties of the materials and the behavior of the failed component and other similar components come under intensive scrutiny. When a collapse has occurred, there will usually be abundant material for testing. However, in cases where a repair of the failure or retrofit of the structure can be made, careful planning in the procurement of materials is essential to minimize additional damage.

For concrete structures, cubes may be cut or cores may be drilled from separated fragments, or cores may be extracted directly from structural members. Although it is desirable, if possible, to obtain 6-in. cubes or 6-in. diameter cores, smaller sizes can be useful for compressive strength tests. Interpretation of the results of a strength test on a cube or a core requires considerable care. Interestingly, however, the strength of concrete is seldom a significant factor in the failure of an existing concrete structure. Petrographic and chemical tests on specimens of the concrete are useful in assessing such characteristics as soundness of the aggregates, degree of hydration of the cement, cement content, air content, and extent of microcracking.

For steel structures, preservation of steel fracture surfaces by coating with a clear sealer is almost always beneficial. However, sealers that have a high residue content should be avoided because of the subsequent difficulty in removing these materials. Close examination of the fracture surfaces must be carried out in a laboratory; therefore it is necessary to remove a piece of the steel material that includes the fracture piece. In general, it is advisable to remove a piece that is also sufficiently large for obtaining specimens for physical and chemical testing.

It is also possible to obtain material for examination and testing by coring through steel plates in the bridge. Previous experience indicates that drilling 3-in. or 4-in. diameter core holes is a simple procedure when the proper equipment is used and that these cored pieces of material can be used for most of the desired physical and chemical tests. These cored holes are no more detrimental to the bridge than are the holes for bolts, provided the edges are as smooth as those of a drilled hole and that the holes are made at a location where they do not reduce the net section more than the drilled bolt holes at other nearby locations. Core specimens, although round rather than square as required for an ASTM compact tension test, serve that purpose extremely well. It should be noted that the compact tension tests are usually performed at the lowest anticipated service temperature and with a loading rate of 1 second to failure.

An ample amount of material should also be obtained for Charpy V-Notch testing. If a subsequent fracture mechanics evaluation is to be made, it is usually desirable to obtain CVN values over the full range of temperatures that may affect a bridge. Performing 3 CVN tests at 8 to 10 temperatures is usually adequate. More tests may be required if there is substantial variability in the material, as has been the case in some investigations.

Tensile tests to determine the yield point and tensile strength of the material will also generally be made on samples of the steel. It is important to note that there is some variation in yield strength with temperature, with the yield increasing as temperature decreases.

Examination of the fracture surface will reveal the direction of propagation of the fracture; mode of fracture and whether ductile, brittle, or mixed; and whether or not fatigue crack growth was evident in the fracture initiation site. The scanning electron microscopes frequently used by commercial metallurgists provide magnifications in the range of 5,000 to 10,000. However, the rate of fatigue crack growth in bridge structures is frequently so small that much larger magnification, of the order of 20,000 to 50,000, is required. Special transmission electron microscopes are needed to examine a fracture surface at this level of magnification. Such examinations will usually reveal the spacing of fatigue crack striations—a vital piece of information in a fracture mechanics evaluation.

Analysis

It is tempting to expect that a careful check of the design will clearly pinpoint the problem after a failure has occurred. However, this is seldom the case. Furthermore, assumptions used in the design process, although often necessary from the point of view of obtaining a safe and durable structure, may not be particularly relevant as far as the in-service conditions experienced by the critical element before failure.

If a design review has been completed without finding significant discrepancies, it is often assumed that a more complex analysis, such as with finite elements, is necessary in order to determine the cause of the failure. Again, such procedures should be viewed with caution because they can be misleading. Instrumentation and testing of similar elements, if available or if a mock-up can be developed, may provide more direct answers. Strain-relief techniques to measure *in situ* stresses should also be considered.

Review of Bridge History

Past events may have an impact on a bridge failure. These events may have occurred during fabrication or construction if it was necessary to revise the design conditions or if conditions not anticipated in the design were encountered. These events may also have occurred during the service life, either as a result of usage or of modification. Cold weather increases the potential for brittle fracture in steel bridges. Aggressive environmental conditions may also lead to corrosion.

CONCLUSION

There are many facets to an investigation of a structural failure, only some of which are discussed in this article. Ideally, the investigation will lead to a clear determination of the cause of the failure. Usually such a determination is a prerequisite for developing, if practical, an effective repair. In reaching this determination, investigators must be objective, while recognizing that their client may have personal interests that they are entitled to protect.

Unfortunately, investigations are too frequently only carried to the point that they serve the interests of the client. It is important that the lessons learned from failure investigations be made available professionally. Investigators should be encouraged to present their conclusions in public forums or in technical papers, where they are subject to peer review.

The Presidential Task Force, under the chairmanship of FHWA's Charles F. Scheffey, that investigated the collapse of the Point Pleasant Bridge called for sufficient fracture toughness in highly stressed steels and either adequate protection against corrosive agents or assessibility for detailed inspection. The task force also recommended upgrading the procedures for conducting structural safety inspections of bridges. Possibly some of the failures that occurred since that time could have been avoided if more attention had been given to the recommendations of the task force.