This article is part of the IEEE Reliability Society 2009 Annual Technology Report.

Major Bridge Collapses in the US, and Around the World

James McLinn
CRE

Abstract
Bridges are basic infrastructure, expected to be reliable by all modern industrial societies. Bridge use and construction have evolved greatly in the last 100 years. Bridge designs range from suspended walkways to five mile long structures. A variety of different construction methods exist ranging from simple piers and wooden timbers to massive cable suspensions. Quality materials, adequate design, and good manufacturing techniques are assumed today, but this assumption wasn't always true 50 or more years ago. In addition, we assume that bridges receive periodic inspection with regular maintenance actions. This regular inspection began in the US after the famous Silver Bridge collapse in 1967 [2], [6]. Before building a bridge, it is important to establish a good understanding of the weak points of bridge design, and the reasons for bridge failure. This knowledge helps focus the inspection on the key elements of the design. Even one high stress event on a key part of a bridge design can often lead to immediate or eventual failure. Most bridge collapses give few warning signs, hence regular inspection is important to validate that a bridge is still safe, and no significant deterioration has occurred. In general, bridges are two-state systems: either reliable, or in the state of collapse. We say, in reliability, that a system with a greater number of components is usually less reliable. The opposite may be true of bridges. The more components present, usually the greater the redundancy will be, the better the design margin of the bridge, and the longer it should stand. There is a body of major bridge failures worldwide, and an even larger body of incidents where failure did not occur, but the bridge needs repair. Both sets of information provide an interesting picture of bridge reliability.

Detail
Look at the recent history of bridges in the US & Canada, Europe, and the rest of the world (International). Table I shows a summary of major bridge incidents since 1970. Three events will be detailed for cause and outcomes. One old reference identified that about 40 bridges per year were failing in the US in 1890 [1], and this had been true for years. Today, with over 690,000 bridges in the US [6], we expect very few bridge failures annually because complex systems are in place to prevent failures. That wasn't true before 1970. The incidence of bridge failures in the US and International was fairly steady until the last 10 years. Europe has been fairly steady over the last 40 years. Recent bridge failures have suggested a potential problem. After the I35W bridge failure of August 1, 2007 in Minneapolis, a quick re-inspection of similar bridge designs in Minnesota led to two others being shut down temporarily for detailed inspection. One of these Minnesota bridges was closed permanently, and then replaced because it shared the same design weakness as the I35W bridge [7].

Table I. A Summary of Reported Major Bridge Failures

Year	US & Canada Incidents	Europe Incidents	International Incidents
1970-1975	1	3	3
1976-1980	1	2	2
1981-1985	3	None	1
1986-1990	4	2	2
1991-1995	2	1	2

1996-1999	1	1	3
2000-2005	7	2	7
2006-2009	5	2	14
Total	24	13	34

Few bridge incidents were reported in the 1950s or 1960s in the US. When the “Silver Bridge“ that connected Ohio with West Virginia collapsed unexpectedly on Dec, 15, 1967 while filled with cars and trucks, a serious re-examination of bridge inspection policy was initiated [1], [6]. This bridge that spanned the Ohio River was less than 40 years old, and had not presented any evidence of deterioration during periodic inspections. Why had it so suddenly collapsed and led to the death of 46 people? Two items might be quickly identified. There was no standard “load limit” on bridges in the US at this time, and the Silver bridge was jammed with traffic. The second item was that the bridge inspections at that time were not regular, and might consist only of a partial inspection of the design elements that could be easily accessed. Some key elements of the Silver Bridge design were more than 40 feet above the bridge deck itself, and these were only inspected with binoculars every few years. No one actually closely inspected key joints at this height of the suspension bridge. Hidden flaws, corrosion, and initial cracks could not be readily identified from the bridge deck. As a result of this bridge failure, detailed, thorough bi-annual bridge inspections were instituted for all bridges in the US (via a 1968 highway law). The formal establishment of a load limit on bridges also forced designers and the state departments of transportation (who were responsible for most bridges) to plan for load limits during the design stage, as well as considering this as part of maintenance. The load on a bridge consists of two items: the “dead load” which consists of the static weight of the bridge itself that must be supported by the piers or cables, and the total “dynamic load” which consists of the total weight of all vehicles actually on the bridge. It is the dynamic load that we see covered by signs marked on the size of bridges indicating a “load limit” for vehicles. With these new US standards, the incidence of major bridge failure remained low for 30 years. Older bridges, built before 1970, did not necessarily meet the new standards, but could be down-rated for lower load limits to handle questionable situations of deteriorating structures. Bridge rating systems were also developed to indicate the state of a bridge based upon the bi-annual inspection.

Table II. A Breakdown of Reported Major Bridge Failures by Cause

Main Causes	US & Canada Incidents	Europe Incidents	International Incidents
Struck by train	1	2	4
Struck by boat	6	1	2
Scour	1	2	1
Collapse during build	1	1	9
Collapse during re-build	1	None	1
Overload	2	None	9
Corrosion	2	None	2
Design error	1	1	None
Flood	1	1	1
Unknown	1	None	2
Other	7	5	3
Total	24	13	34

Table II shows a basic breakdown of the causes of major bridge failures. The two biggest causes in the table are the nine incidents of collapse during original bridge construction, and the nine incidents of bridge overload. Both were in the International geographical region, and totaled slightly over half of the bridge failures since 1970. The third highest entry was the 6 incidents of being "struck by a boat," all of which occurred in the US. The next highest entry is 4 incidents of "struck by train" in the International region. Next, there were 2 overload incidents in the US, one of which was a walkway in Kansas City. We can conclude that bridges are susceptible to being struck by large objects, as such incidents were responsible for about 25% of all bridge failures.

In some cases, there would be multiple interacting events to cause a bridge failure. For example, corrosion combined with overload might take down the bridge. The other common interactive cause is bridge scour. That is, the pillars or piers holding up the bridge might be undercut by a flood, and lead to a collapse from heavy loads.

The trends in time reaffirm these observations over 39 years. In the US & Canada, three of the 10 failures since 2000 were "struck by boat or truck" (hereafter, just "struck"). The remaining seven failure causes are each unique. In Europe, since 2000, two of four bridge failures were of the "struck" cause. In the rest of the world, two of 21 failures since 2000 were of the "struck" cause, whereas eight were overload situations, and seven were construction-related collapses. These results suggest that causes may not be changing over time.

A breakdown by country shows the US with the most major failures at 22 over the 39 year period, with a population of bridges in excess of 690,000. During the same period, India had 5 failures, Japan had 4, followed by China, Germany, and the United Kingdom with 3 each. Canada, Nepal, Russia, Korea, and Pakistan each experienced two failures. The main cause of US bridge failures was "struck," which accounted for seven, or about 1/3 of all US failures. India had five different reasons for bridge failure. These were flood, overload, terrorist action, fell during construction, and fell during re-build. Japan with four total failures had two walkways collapse caused by people overload, one for storm, and one bridge that had not been inspected for 10 years collapsed from corrosion. Based upon these results, the remaining focus will be upon causes of bridge failures in the US.

Wardhana et. al.[6] performed a study of all bridges events in the US, which included four categories ranging from simple bridge distress, partial collapse, total collapse, and unknown. These were gleaned from a variety of sources, and spanned 1989 to 2000. The top level results are shown in Table III. This study included many more bridge events (536 total events) than the study of Table II. The results reflect the major flood years of 1993 and 1996 in which many bridges were somewhat damaged or placed in distress. These data again show that external events are a bigger cause of bridge problems than design or construction. The breakdown by state indicated Maryland (0.49%), West Virginia (0.42%), and Iowa (0.33%) had the highest percentage of bridge problems over the 11 study years.

Table III. Breakdown of Events, US Only, Wardhana et.al.

Category	**Percent**	**Percent**
Flood	165	32.8%
Scour	78	15.5%
Collision	59	11.73%
Overload	44	8.75%
Deterioration	43	8.55%
Earthquake	17	3.38%

All three tables combined suggest the following conclusions.

1) The incidents of major bridge failures have been increasing in the US, as well as the rest of the world, in the last 9 years. In the US & Canada, and Europe, bridge failures have increased by about a factor of 4 compared to the prior 10 year period of the 1990s. The rest of the world only doubled during the same periods.

2) "Struck" seems to be the biggest cause of major bridge failure in the US. When minor bridge events are included, flood and scour were the biggest causes of bridge problems in the US.
3) Overload was the second largest reason for major bridge failure in the US.
4) "Struck" was a minor problem of major bridge failure in the International region, and important in Europe.
5) Worldwide, overload was the biggest cause of major bridge failure at nine incidents.
6) Worldwide, collapse during construction was the second biggest cause of major bridge failure at nine incidents.
7) The "struck" cause was third in the US study of all bridge events from 1989 to 2000.

The tables suggest there are systematic causes of failure still present that lead to bridge collapse. This is true of the US & Canada causes, where information is better known. After struck by, corrosion, and overload, all of the other causes of failure in the US have only one incident of major bridge failure. The Wardhanna study [6] shows overload and deterioration as causes after flood, scour, and collision. These causes should have been addressed through periodic inspection.

The famous August 1, 2007 I35W bridge collapse in Minneapolis is still under investigation, but several contributing causes seem present. The first is that the dead load on the bridge had been increased during an earlier update of the bridge that added walkways. In 2001, a study by the Civil Engineering Department of the University of Minnesota found some cracking in cross girders of the approach spans. These cracks were quickly repaired. In 2005, the Fed DOT rated the bridge as "structurally deficient" giving it a score of 50 out of 100 (about 10% of bridges score this low annually). An inspection on June 15, 2006 found additional cracking, and further evidence of fatigue in the structure. Trucks, materials, and equipment totaling approximately 575,000 pounds were on the bridge at the time of collapse, as well as 4 of the 8 lanes of jammed traffic during the rush hour. A post collapse investigation in 2008 identified the gusset plates, which hold the bridge deck sections to the pier, as being half of the proper thickness for the bridge load rating. The bridge had stood for almost 40 years that way. It took both of these problems, the combined load of rush hour traffic with many heavy work trucks on the bridge during the ongoing rebuild, to cause sudden structural failure [3]. Could this failure have been prevented? The best answer is "possibly." Eliminate any one of the two heavy load factors, and the collapse might not have occurred that day. A final report is still pending.

Many bridge professionals question the inspection policy for bridges as a way to ensure bridge reliability. One professional [4] stated "To ensure that the scarce resources available for maintaining the US bridge inventory are spent in an optimal manner, bridge management programs have been mandated by the Federal Highway Administration. However, these programs are mainly based on data from subjective condition assessments, and do not use time-variant bridge reliability for decision making. Many nondestructive test methods exist for the detailed inspection of bridges. Predictions based solely on inspection data may be questionable, particularly if limitations and errors in the measurement methods that are used are not considered".

The recent problems with the Oakland Bay bridge document the value of the regular inspection process [5]. In 1989, this bridge had been damaged by the October earthquake. After years of study, a decision was made in 2004 to replace this eastern span with a $6B deck bridge. Work on replacing this eastern span began in 2007. On Sept. 2, 2009 some eye-bar cracks were found on the eastern span of the Bay Bridge (which carries 280,000 vehicles a day) during the regular bi-annual inspection. The bridge was closed, a quick repair was made over the Labor day weekend, and the bridge reopened September 8. On October 27, 2009, a crossbar, and tension rods weighing 5000 pounds crashed to the bridge deck. These had been part of the Labor day repair. Improved welds and cross ties were then added, as well as protective sleeves and strain gauges. The bridge was reopened after 8 days of repairs. The events described show that regular inspection can be effective at identifying a deteriorating bridge situation, and preventing a more serious collapse.

Conclusions

Based upon a survey of studies, and a few famous bridge problems (Silver, I35W, and Oakland Bay), we can conclude that most bridges are impacted by outside events (flood, collision, etc.), and the intrinsic bridge problems of design, corrosion, and deterioration occur less frequently with less serious results, but are not negligible. A review of bridge events also strongly suggests that inspections may need to be improved, and that inspection alone is not sufficient to guarantee bridge reliability because it does not include all time-dependent failure modes and causes.

References

[1] *Bridge Disasters in America: The Cause and the Remedy*, Vose, George L., Lee & Shepard, Boston, 1887

[2] Silver Bridge Failure details can be found at http://35wbridge.pbworks.com/Silver+Bridge+Collapse

[3] http://en.wikipedia.org/wiki/I-35W_Mississippi_River_bridge

[4] Popela, Pavel, ASCE *Journal of Structural Engineering*, Vol. 125, No. 10, October 1999, pp. 1118-1125,

[5] http://en.wikipedia.org/wiki/Eastern_span_replacement_of_the_San_Francisco_%E2%80%93_Oakland_Bay_Bridge

[6] Wardhana, Kumalasari and Hadipriono, Prof. Fabian C., Analysis of Recent Bridge Failures in the United States, Journal of Performance of Constructed Facilities, ASCE, August 2003, pp144-150

[7] St Cloud Bridge Potential Failure, http://www.startribune.com/local/16894261.html