Bridge Disasters: What we do, and do not learn from them

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I recently read Monobina Gupta's August 4, article on the Mahad Bridge Collapse on First Post India's website (http://www.firstpost.com/india/mahad-bridge-collapse-indias-developmental-priorities-are-skewed-and-wrong-2934338.html). As an engineer involved in bridge design, inspection, rehabilitation, and monitoring, I also have given some thought to the collapse of Mahad Bridge and the flyover collapse in Kolkota earlier in the year. The two events are different in the sense that the Mahad Bridge collapsed after being in service for decades, while the Kolkota Bridge collapsed during construction. Records indicate that the most of the bridge failures have occurred during construction. The collapse is sudden, and its cause is known only after the event has occurred.

Any structure-failure evokes strong public reaction in its immediate aftermath. However, after a brief period of frantic activity the event is forgotten until the next disaster. I believe it is time that politicians of all stripes, bureaucrats, and the engineers came together and addressed this ongoing threat to public safety due to their combined inaction. This is not to say that bridge failure will not ever occur thereafter, however, we can at least eliminate the risk of bridge collapses due to neglect or the lack of proactive measures. In the following, I have presented a historic context on bridges, identified some of the primary causes of distress in bridges, and suggested a course of action that should help to significantly reduce potential risks.

Defining Failure

A bridge failure does not necessarily mean a complete collapse, but also includes its inability to perform one or more of its intended functions.[1] However, if the bridge were still in use despite partial loss of functionality, the probability of a disaster would increase significantly.

There have been several publications over decades exploring the causes of bridge failure. I would like to present excerpts from two publications, which in my view are quite relevant, even in today's world.

"Nearly all of the disasters which occur from the breaking down of bridges are caused by defects which would be easily detected by an efficient system of inspection."[2] Although published in 1887, in light of the recent history of bridge collapses, the author's words are just as relevant today.

M. H. Tweed wrote, "Failures are very often due to lack of inspection or the economics involved in a particular project which leads to carelessness or neglect. Many major bridge failures in this report are primarily caused by lack of inspection." and, "Most of the failures in completed structures are a result of dishonest performance and noncompliance due to ignorance or a matter of economics rather than improper design."[3]

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[1] "Bridges – Analysis, Design, Structural Health Monitoring & Design; Mufti, Bakht, & Jaeger, 2nd Ed, 2015, Springer

[2] "Bridge Disasters in America - The Cause and the Remedy" by George L Voss, 1887

[3] "A Summary and Analysis of Bridge Failures" Master's thesis submitted to Iowa State University in 1969 by Maynard Horace Tweed

He listed the following common causes of bridge failure:

1. Ignorance: a. Incompetent men in charge of design, construction or inspection; b. Supervision and maintenance by men without necessary knowledge or experience; c. Lack of sufficient preliminary information; and, d. Revision of design by persons lacking knowledge of the original requirements.
2. Economy: a. Restrictions on initial cost; and, b. Lack of maintenance.
3. Carelessness during construction: a. An engineer, usually competent and careful, shows negligence in some part of a design; b. A contractor takes a chance while completely aware of the risks involved; and, c. Lack of coordination in production of plans, construction, procedures and inspection.
4. Unusual occurrences.

Although, some failures could be attributed to the forces of nature, it is quite apparent from the aforementioned that a bridge failure typically is a direct result of actions or inaction of human being.

Causes of Failure

A bridge failure can result from one or more of the following reasons.

1. Advanced age,
2. Deterioration, and degradation,
3. fatigue,
4. Increased traffic volume and vehicle weights,
5. Natural calamities and man-made disasters,
6. Deficiencies in design codes,
7. Construction flaws, such as substandard materials, workmanship, construction practices,
8. Inadequate inspection during construction,
9. Lack of periodic and thorough inspections,
10. Inadequate/deferred maintenance,
11. Ignored or overlooked signs of distress.

Historic Context

Before we look at improving the way the bridges are being managed presently, let us place the issue within historical context. With respect to India, we can divide highway bridges in three distinct groups according to their vintage. The first group comprises the bridges constructed during the British rule, the second group includes bridges constructed post-independence up to 1980s or thereabout, while the third group includes the bridges designed using sophisticated design software and constructed utilizing latest construction techniques. The bridges in the first two groups deserve the most attention; however, the bridges in the third group also have potential to raise concerns after a decade or two in their service life.

British Era Bridges

The bridges constructed during the British era were designed for vehicles that were significantly smaller and lighter than those on the road today. The total traffic volumes were also very low. Many of those bridges were of stone or brick, masonry arch construction. The fact that those bridges are still in service carrying ever-increasing volumes of heavier loads, can be attributed to,

a) Their structural form, i.e. a masonry arch, in which the main components of the arch bridge are predominantly in compression, and the material in compression (unless deteriorated), does not lose its strength over time.
b) The factors of safety adopted in the design were too large as the engineers then were uncertain of the failure mechanism of the structure.
c) Better quality control procedures coupled with a slower pace of construction.

These bridges are, however, decades past their intended service life, and need to be closely monitored and replaced in a planned manner.

Post-Independence Construction

Post-World War II/post-Independence era saw a phenomenal increase in the construction of highway bridges in the world, including North America, Europe, and India. There has been a significant increase in the gross vehicle weight (GVW) of trucks, and the truck traffic volumes since their construction. We must not forget that this was also a period of perpetual shortage of Portland cement and reinforcing steel in India, the two key materials necessary for bridge construction, which may have led to the contractor cutting corners, leading to sub-optimal construction quality. The bridges that are in the coastal region are also prone to accelerated deterioration due to the ambient marine environment. A large inventory of such bridges, structurally deficient to varying degrees, has reached the end of their anticipated service life, and will require significant investment for repairs, rehabilitation, or replacement in the near future.

Concerns Over newly constructed bridges

With its phenomenal growth over the last few decades, highway transportation has become a key contributing factor in India’s economic growth. During my annual visits to India over the past several years, I keep passing new bridges and flyovers under construction in practically every city that I visit. Being a bridge engineer myself, I never tire of looking at the solutions the bridge designers come up with to address the challenges that they encounter. Sometimes, the solutions are quite elegant, while some appear to be just adequate. While a new bridge is not expected to require significant maintenance or repairs during the initial decade or two, maintaining it in good health over the remainder of its service life requires adequate resources and timely intervention. That being said, with such a tremendous growth in the highway infrastructure there will come a time that a sizeable proportion of the bridges and overpasses will require significant investment over decades to come. So, footing the bill becomes a matter of primary importance.

Adequate and safe access is one of the major challenges in inspecting and maintaining the new generation of bridges. Inspectors require special equipment to access hard to reach areas for inspection at close quarters, and their lack may result in the inspections being either deferred, or cancelled altogether. A large number of flyovers span over congested local roads, and the sheer volume of local traffic may prevent inspectors from fulfilling their mandate.

Weaknesses are inherent in any given infrastructure network, as are the associated risks. Risks can be managed and minimized by implementing a well-designed bridge management plan. The primary objective of any risk management strategy is to ensure public safety, with the secondary objectives being protection of national assets, and maintaining public confidence in the infrastructure system that is critical for uninterrupted economic growth.

On Arch Bridges

The recent collapse of the masonry arch bridge in Mahad on Mumbai-Goa Road has focussed attention on the safety of similar bridges in other parts of the country. Masonry arch bridges transfer loads imposed by traffic to the abutments and piers by arching action. In plain language, starting from the keystone of the arch, each stone block transfers the load to the block immediately below by exerting pressure on its face of contact, and finally the entire load is progressively transferred to the arch supports on either side. As long as the joints between the stone blocks in the arch, as well as the supports, are intact, the arch will function as intended. If the integrity of the arch or the piers is compromised, as evident from the trees growing out of undamaged arches and piers of the collapsed bridge, failure is possible under certain adverse conditions.

We must not, however, overlook the fact that these arch bridges were designed for significantly lower loads based on the vehicles that were in use at that time. The design vehicles used in North America in early 1900s were a two-axle truck, a road roller, and/or a uniformly distributed load. In the intervening years however, the gross vehicle weight of trucks and the traffic volume have steadily increased and are far in excess of original design.

There are examples of several historic masonry arch bridges in service all over the world. Some of the oldest masonry arch bridges in the US are Penneypack Creek Bridge, in Philadelphia, Pennsylvania, (1697), and Choate Bridge in Ipswich, Massachusetts (1764).

Where do we start?

The following multi-step process is suggested to improve the way the bridges are managed:

1. Adopt a standardized bridge inspection program that will eliminate or minimize inspector subjectivity in grading,
2. Train and certify a cadre of bridge inspection professionals through accredited classroom and field training program,
3. Mandate that inspections are carried out only by certified inspection professionals ,
4. Mandate periodic recertification of inspection professionals,
5. Inspect and identify bridges at risk and categorize them in order of severity of the risk,
6. Identify Structural deficiencies of bridges at risk, and monitor through a combination of visual inspection, automated survey, and Structural Health Monitoring (SHM),
7. Analyze at-risk bridge structures using SHM data for parameters such as strain displacement, rotation, etc. rather than by using prescribed theoretical values,
8. Schedule frequency of future inspections according to their risk category,
9. Where access is a major hurdle in inspections, utilize drones to carry out quick inspection of the bridge, or to inspect hard-to-reach bridge elements at close quarters. This may require ground training for drone operators and permission from the Directorate General of Civil Aviation (DGCA) and other concerned authorities,
10. Harness the power of electronic media to engage public in reporting their concerns regarding safety or integrity of bridges in their vicinity, and
11. Provide adequate resources for bridge inspection, maintenance, rehabilitation, and replacement.

In Canada, many jurisdictions use the Ontario Structures Inspection Manual, generally known as OSIM, or a variation thereof, for their bridge inspection program. Adopting stricter training and certification requirements for bridges inspectors has also resulted in significant improvements in their bridge management program.

Can SHM application help identify abnormal behaviour or unsafe conditions?

At this point, a brief discussion on Structural Health Monitoring (SHM) becomes necessary. The American Society of Civil Engineers defines SHM as “a tool to detect, locate, and assess damage produced by severe loading and environmental deterioration through strategically placed sensors.” An SHM system comprises an array of sensors connected to a central data collection device and a data communication module to transmit data to a base station for processing, review, and analysis. The concept of instrumented monitoring has been in use for decades in aerospace, aviation, and automotive and medical fields. Recent developments in electronics and wireless communication have made monitoring of structures, even at remote locations, viable. SHM application requires expertise in structural engineering, as well as in instrumentation techniques, programming, and wireless communication.

An SHM system on a bridge is quite similar to the equipment used for conducting stress test in hospitals. In a typical stress test, the blood pressure, heart rhythm, and breathing are monitored by means of an array of sensors attached to a patient’s body, while they walk on a treadmill or pedal a stationary bicycle. Doctor can then review the test data and form an informed opinion on the state of patient’s heart. SHM system is similarly used to monitor key parameters of a bridge structure by attaching appropriate sensors at key locations and monitor its behaviour under traffic, wind or other loads.

In another scenario, a patient in ICU is hooked up to a monitoring system which generates an alarm should any of the vital organs cease to function. An SHM system can also be designed to generate alarms should any of the critical functions of the bridge are compromised.

SHM application, in the context of the Mahad Bridge collapse would be topical. Under SHM, electronic sensors are placed at locations where certain parameters are expected to be critical. For example, on the spandrel wall, if it is suspected that excessive loading from the traffic load is causing the spandrel walls to gradually lean out, and could lead to their eventual failure, if remained unchecked. In this situation, tilt sensors could help monitor the progression of the wall tilt and then appropriate measures could be taken, if needed. Similarly, relative movement between adjacent stone blocks in the arch or the supports could be monitored by placing displacement sensors. Unusual deformation of the arch soffit, or the bottom surface can also be monitored by means of convergence meters or similar devices. In certain situations, the arch surface can also be monitored by installing surveying target along the periphery of the arch and gathering survey data using a Total Station or similar device.

Structural Health Monitoring has been gaining ground as an important risk management tool to monitor and manage important infrastructure assets and structures of strategic or historical importance. SHM allows owners and engineers to monitor key parameters of structures such as a bridge or a building on an ongoing or periodic basis remotely. An SHM system can generate warning alarms in case any of the parameters being measured exceeds a predefined limit. For example, if the vertical movement of a bridge girder exceeds a predefined value, the system will automatically generate and send alerts through emails or text messages to the person/s responsible. The message will include details such as, the time the event occurred, and the recorded value of the parameter that triggered the alert. This will help the recipient respond appropriately in a timely manner.

Highway Bridges v/s Railway Bridges

While writing this article, one of my professional colleagues in India sent me an article published in a recent issue of Maharashtra Times. The article was written by Mr. Pradeep Mhetre, retired Assistant Executive Engineer, Central Railway. His article provides valuable insight on the management of railway bridges in India. Railway bridges in general, are better managed and maintained than their highway counterparts in most countries. A review of recorded bridge failures indicates that majority of the railway bridge failures seem to be the result of a derailment or collision on the bridge, or from a vessel impact to the bridge substructure, while structural failures due to design errors seem to be minimal.

The main difference between the highway bridges and the railway bridges lies in the spread of the infrastructure. Railway infrastructure is linear or unidirectional where all the bridges are distributed along a particular railway route. Hence, it is easier to sectionalize, access, inspect, and manage them in an effective manner. In contrast, the highway infrastructure is inherently a multidirectional network and requires significantly greater human and financial resources to be at par with the management of railway bridges.

The other factor that also works in favour of the railway bridges is their well-defined load regime as compared to the highway bridges. The loads imposed by locomotives and the wagons are known and controlled with greater degree of certainty, hence no surprizes, and the bridges can be evaluated and upgraded well in advance before the induction of heavier rolling stock into service. In comparison, there is a significantly greater variability in the load patterns on highways bridges and overloading can occur and go undetected. Research has shown that an overloaded truck can cause more damage in a single pass than that caused by a hundred thousand or more passes of a lighter vehicle going over the same bridge.

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His company's primary focus is on bridges, marine structures, and Structural Health Monitoring (SHM). His company has recently developed capabilities in the use of drones for structural inspections as part of promotion of innovative materials and technologies.