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I-35W Mississippi river bridge failure – Is it a wake up call?

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Infrastructure plays a major role in the economy of a country. Bridges are a major component of any infrastructure and the failure of a bridge will affect the economy of any country. The recent failure of the I-35W Mississippi river bridge may be considered as a wake up call to think about redundancy in structural design of bridges, and evolution of bridge monitoring and inspection systems. The details of the I-35W Mississippi river bridge, its failure and its impact on future bridge designs, monitoring and testing are discussed in this paper. These details may help in preventing such disastrous failures in future.

Henry Petroski, a designer and a professor of civil engineering at Duke University, U.S.A., has extensively studied spectacular design failures, and predicts that failures lead to major progress. He is also known for popularising the theory that there is a major bridge collapse every 30 years. Extrapolating from the West Gate bridge disaster in 1970, the world was due for another major collapse in 2000[1]. But, the recent I-35 W bridge failure came seven years late. The theory first appeared in a 1977 paper in the Proceedings of the Institute of Civil Engineers by civil engineers Paul Sibly and Alastair Walker. They based their theory on observations of the pattern of major bridge collapses: the Dee in 1847, the Tay in 1879, the Quebec City bridge in 1907, the Tacoma Narrows in 1940 and the West Gate in 1970. Whether this theory will hold well in the near future is debatable as many of the aging infrastructure projects in several countries are under threat of failure and some immediate measures are necessary to save them from disasters. This paper discusses the recent failure of I-35 W Mississippi river bridge and gives some details of other major bridge failures.

The I-35W Mississippi river bridge

The I-35W Mississippi river bridge (officially designated Bridge 9340), which opened in 1967, was an eight lane, 579 m long steel truss arch bridge (with steel multi-girder approach spans) that carried Interstate 35W across the Mississippi River in Minneapolis, Minnesota, United States. The bridge, maintained by the Minnesota Department of Transportation (Mn/DOT), was Minnesota's second busiest, carrying 141,000 vehicles daily. This bridge carried nearly 25% of the traffic into downtown Minneapolis. Construction of this bridge began in 1964 and the bridge was opened to traffic in 1967 (Figure 1). Original cost for the bridge was US$ 440,740 to construct the piers and US$ 4,828,262 to construct the bridge. As the average life span of a deck steel truss bridge is considered to be about 50 years, compared to a 75-100 year life span of a typical prestressed concrete bridge, it was scheduled for reconstruction in 2020-25.

Figure 1. The I-35W Mississippi river bridge - Before and after failure

Design details of I-35W bridge[2]

The bridge was designed by Sverdrup & Parcel as per the 1961 American Association of State Highway Officials (AASHO, the precursor to AASHTO) standard specifications. Hurcon Inc. and Industrial Construction Company were the construction contractors with Industrial Construction Company building the steel trusses and deck. The bridge work was commenced in 1964 and completed in 1967. It was the last new river crossing built in Minneapolis.

The bridge was over 579 m long and consisted of fourteen spans: five south approach spans, three main spans and six north approach spans. The three main spans were of deck truss construction while all but two of the approach spans were steel multi-girder construction with the remaining two approach spans being concrete slab construction. The bridge had no piers built into the river bed. Instead, the centre (river) span of the bridge consisted of a single 140 m steel arched truss over the 119 m wide navigation channel. There was no redundancy in the main truss system, meaning that a single structural failure could have catastrophic consequences. In a redundant system, another structure would have absorbed the load if one of the deck stresses failed due to a combination of distortion and aging materials. Truss-type designs date all the way back to the late 18th century, but have fallen out of favour since 1970 as better highway construction materials (prestressed concrete and steel plate girders) have emerged.

The approach span superstructures were supported by 14 continuous 1219 mm deep welded plated girders (five approach spans were at the south and six approach spans were at the north). Spans 6, 7 and 8 were the main river spans and the traffic loads were supported by two steel deck trusses parallel with traffic. The two support piers for the main trusses, each with two load bearing concrete pylons at either side of the centre main span, were located on opposite banks of the river. The centre span was connected to the north and south approaches by shorter spans formed by the same main trusses. Each was 81 m in length, and was connected to the approach spans by an 11.6 m cantilever.

The two main trusses, one on either side, ranged in depth from 18.3 m above their pier and concrete pylon supports, to 11 m at mid-span on the central span and 9.14 m deep at the outer ends of the adjoining spans. At the top of the main trusses were the deck trusses, 3.66 m in depth and integral with the main trusses. The transverse deck beams, part of the deck truss, rested on top of the main trusses. These deck beams supported longitudinal deck steel beam stringers 686 mm in depth, and reinforced concrete pavement. The deck was 34.5 m in breadth, and was split longitudinally and also had transverse expansion joints at the centres and ends of each of the three main spans. The roadway deck was approximately 35 m above the water level.

Bridge bearings, such as the multiple roller bearings were used in the bridge to transfer loads from the deck to the superstructure. Their primary purpose is to redistribute major longitudinal shifts in load. Elastomeric and fluoropolymer materials are sometimes used in bearing systems, but often for different purposes than the steel system used on the Minneapolis Interstate bridge. It is likely that engineers will put fresh emphasis on potential use of polymeric materials as a result of the calamity in Minneapolis.

Figure 2. Two different views of the I-35W bridge failure

Collapse of the I-35W Mississippi river bridge

During the weekday evening rush hour on August 1, 2007, with the bridge traffic moving slowly through the limited number of lanes, the central span of the bridge suddenly gave way followed by the adjoining spans. The structure and deck collapsed into the river and onto the river banks below, the south part toppling 25 m eastward in the process. Approximately 100 vehicles were involved, sending their occupants and several construction workers up to 35 m down to the river or onto its banks, Figure 2. Northern sections fell onto three unoccupied and stationary freight train cars sitting in the rail yard in that sector. Thirteen people died and over 100 people were injured because of this incident.

Causes of failure and earlier investigations

National transportation officials said that it is too early to know exactly what caused the bridge to give way. The bridge has been inspected annually since 1993 and every other year prior to that. The state reports from 2001 and 2005 indicated there were fatigue cracks in the bridge's trusses, and that the bridge had no secondary system to bear the weight of traffic in the event of an unexpected failure[2, 3]. It was scheduled for reconstruction in 2020 - 2025 according to the Minnesota Department of Transportation.

The bridge was identified as the single most treacherous cold-weather spot in the Twin Cities freeway system due to a thin layer of black ice causing spinouts and collisions on the bridge during extremely cold weather. In October 1999 the state embedded temperature activated nozzles in the bridge deck to spray the bridge with potassium acetate solution to keep the area free of winter black ice.

In 1990, the federal government gave the I-35W bridge a rating of 'structurally deficient', citing significant corrosion in its bearings. "Structurally deficient" is a classification term, which does not in itself indicate a lack of safety; over 75,000 other U.S. bridges have this classification! Seven years later, significant out-of-plane distortion was noted in the main trusses connected to cross girders due to resistance to motion at the connection cross bearings, according to a report released by the University of Minnesota civil engineering department. The cracks in the girders were drilled to prevent further propagation. Support struts were also added to the cross girder.

In 2005, the bridge was again rated as 'structurally deficient' and in need of replacement, according to the U.S. Department of Transportation's National Bridge Inventory database. The scale used was a 'sufficiency rating' which ranges from the highest score, 100, to the lowest score, zero. A score below 80 indicates that some rehabilitation may be needed, while a score of 50 or less shows that replacement may be in order. The I-35W bridge was given a rating of 50 in the year 2005. Out of 104,348 heavily used bridge structures (those with more than 10,000 vehicles travelling on them per day), only 4,227 or 4%, scored below 50, according to an analysis of federal records by MSNBC.

A research report published in March 2001 based on site studies conducted during 1999 and 2000 noted that "although fatigue cracking has not occurred in the deck truss, it has many poor fatigue details on the main truss and floor truss systems." Researchers from the University of Minnesota, Department of Civil Engineering concluded at that time, "The detailed fatigue assessment shows that fatigue cracking of the deck truss is not likely. Therefore, replacement of this bridge, and the associated very high cost may be deferred." No time frame for deferment is mentioned.

The 2006 report found that five main truss members were prone to fractures and should be retrofitted with high performance steel and high strength bolts. The retrofit, according to the study, would enhance the redundancy of truss members and the deck replacement on the main truss spans would reduce live load stresses and enhance the redundancy of the truss system. It also noted several instances of poor weld details, section loss, pitting, flaking, corrosion (including corrosion of expansion bearings - see Figure 3), and cracks (many previously drilled out and braced), among other problems. The bridge "exhibited several fatigue problems, primarily due to unanticipated out-of-plane distortion of the girders. Numerous fatigue cracks were noted in the approach spans".

Progressive Contractors Inc. (PCI) began a US$ 2.4 million project to repair sections of the heavily travelled highway, few weeks prior to the collapse. The repair was minor and cosmetic, focusing on replacing lighting, concrete and guard rails, and some work on joints. The bridge roadway slab was 230 mm thick. As part of the concrete work, the contractor milled (ground) off the top 50 mm of concrete and replaced it with new concrete. Other concrete removal work was done using 20 kg jackhammers. Nothing larger was used to remove the concrete. The most recent jack hammering of deteriorating concrete had occurred the day before and none was performed on the day of the accident. According to the contractor, the work was being done in segments, using industrial saws to cut around damaged sections of concrete and then using jackhammers to remove the severed chunks. At the time of the collapse, four of the eight lanes were closed for resurfacing.

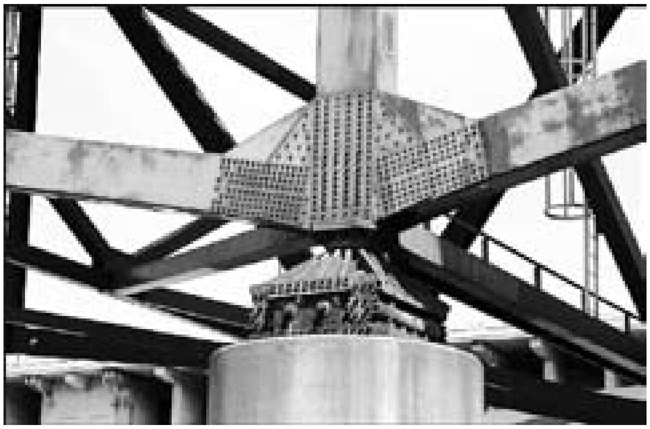

Figure 3. Corrosion of members and bearings of the I-35W bridge

After the failure, the National Transportation Safety Board (NTSB) together with the Federal Highway Administration (FHWA) conducted a structural analysis of the bridge using computational finite element analysis methods. Data collected at the accident scene, including a 3-D laser scan, were used in the computer model to further refine the model. Within 24 hours of the bridge collapse, AERO-METRIC, Inc., Maple Grove, Minnesota, said it had completed a vertical aerial photography mission and an airborne LIDAR (Light Detection and Ranging) mission over the site.

NTSB investigators noted a design issue at particular locations with gusset plates that tie steel beams together. They conducted investigations verifying the loads and stresses on the gusset plates at these locations as well as the materials used in constructing the plates.

The NTSB is also investigating whether resurfacing operations played any role in the collapse, in particular, the extra weight of construction equipment and material stockpiles on the bridge. NTSB is reviewing construction records to determine the location of construction equipment and construction materials on the bridge at the time of the collapse and verifying the weights of those vehicles and materials. The Board also obtained core samples of the bridge deck material to get a better picture of the deck thickness to help make an assessment about the amount of concrete on the bridge at the time of the accident.

By chance, an employee of the NTSB had written his doctoral thesis on possible failure scenarios of this specific bridge while he was a student at the nearby University of Minnesota. That thesis, including his computer model of the bridge for failure mode analysis, is also being used by the NTSB to aid their investigation.

The list of possible causes remains lengthy in the early stages of the investigation. It includes a lack of redundancy in the bridge design, aging steel, rotting welds, vibration from adjacent train tracks and even the corrosive effects of bird droppings.

The area of the bridge's south abutment was a site of industrial chemical pollution. Hence, there was also corrosion of members especially at the bearings (Figure 3). In fact, 13,600 tonne of contaminated soil were removed from below the bridge, ground up with wood chips and burned as a fuel additive for a power plant between 1993 and 1998 at a cost of US $30 million.

NTSB which investigated the bridge failure has recently concluded that the gusset plates which connected the steel beams of the bridge were roughly half the thickness than they should have been and hence contributed to the failure of the bridge. NTSB investigators found 16 fractured gusset plates from the bridge's centre span. Their investigation found no evidence that cracking, corrosion or other wear 'played any role in the collapse of the bridge.' They also found no flaws in the steel and concrete material used in the bridge.

Reactions from civil engineers

Zdenek Bazant, a professor of civil and environmental engineering at Northwestern University, said, "The bridge must have been near a state of collapse for some time, and the construction (activity) might have contributed to its failure." Ohio State University professor Fabian Hadipriono studied all 503 documented bridge failures in the U.S. between 1989 and 2000 for the American Society of Civil Engineers. "It's a time bomb," Hadipriono said. "It's going to happen again if something isn't done to maintain these bridges. It's not a surprise. We're lucky it hasn't happened sooner."

If one of the 10 pins connecting each truss to the roadbed or deck failed, the entire bridge would collapse, said David Billington, a professor of structural engineering at Princeton University. "The pins carry vertical loads down. … If one pin fails, the whole structure fails," Billington said. "There are two trusses. If one truss goes there is no way the bridge can stand up. The deck cannot be supported on only one side." He felt that the design of the bridge was "not generically bad but susceptible to total failure if one part fails. There is, however, no history of this kind of structure failing," he said. According to him, said many bridges across the United States need regular maintenance and he compared the 'structurally deficient' rating to a grade of "C- or D."

Figure 4. Tacoma Narrows bridge in Tacoma, Washington, 1940

Corrosion too could be a factor, said John M Hooks, director of the Bridge Management Information Systems Laboratory at the Department of Transportation Turner-Fairbank Highway Research Center. "In a metal structure, collapse could be caused by fatigue and multiple occurrences of stress or corrosion," Hooks said. "Most bridges are built with a lot of redundancy in them and the members are pretty thick. Fatigue cracks are closed most of the time and may easily be hidden by paint, rust or dirt. In such cases visual inspection would be pretty well useless. You need something that will see inside the steel such as x-rays or ultrasonic." The Interstate 35 bridge was expanded from four lanes to six, and eventually to eight. Some wonder whether that might have played a role in its collapse.

Officials with the Department of Homeland Security said there was no indication that terrorism was involved. The Federal Highway Administration also advised states to inspect the 756 U.S. bridges of similar construction. St. Louis County in Missouri closed one such bridge as a precaution. Mn/DOT hired consulting firms Wiss Janney Elstner and Lichtenstein & Associates to develop a plan for forensic analysis of the cause of the bridge collapse.

A website dedicated to the I-35W bridge collapse and rebuilding — www.DOT.state.mn.us/i35wbridge— contains up to date information, as well as background information on the bridge, including expenditure and inspection schedules, recent inspection reports and studies, inventory reports and lists, and historical reports and drawings.

Worst bridge collapses

Tacoma Narrows bridge in Tacoma, Washington, 1940

High winds caused the Tacoma Narrows Bridge (nicknamed Galloping Gertie) to sway, undulate and finally collapse under the strain on November 7, 1940. No one was injured in the collapse. The final destruction of the bridge was recorded on film by Barney Elliott, owner of a local camera shop. The engineers learned their lesson from studying this film and conducting wind tunnel tests and included some slight modifications to avoid the resonance phenomenon that caused this bridge to fail. The first replacement bridge opened in 1950 and a parallel bridge opened in 2007. It may be interesting to note that a similar lateral vibration (resonant structural response) was noticed in the Millennium foot bridge, London due to the synchronised walking of pedestrians.

Silver bridge, West Virginia, 1967

There are many historical examples of major bridge failures, but one that comes fast to mind today is the 1967 collapse of 533.4 m span, 41 year old Silver bridge across the Ohio river at Point Pleasant, West Virginia. Silver bridge - which took its name from the color of its paint – was a chain suspension structure that collapsed suddenly in rush-hour traffic on December 15, 1967, sending 75 vehicles into the water, killing 46 people and injuring hundreds of others.

The suspension bridge was similar to the Golden Gate bridge in San Francisco and the Verrazano-Narrows bridge in New York City. But instead of spun-wire cables used to hold up the support towers on those bridges, the Silver bridge was held up by carbon steel chains that were anchored on each shore of the river. The bridge had no load limit and at the time of failure, 37 vehicles were on the Ohio side, including five tractor-trailers and a pair of gravel trucks.

It was a year and a half before the Federal Highway Administration issued a definitive report, which attributed the collapse to the growth of an undetected crack in one of the enormous chain links. Aided by corrosion and the repetition of traffic loads over the years, the fatigue crack had grown to such a size that it weakened the link until it could no longer hold up the load it was designed to take. A joint supporting a chain snapped on the north side, toppling both towers and sending the bridge into the water. The heavy load brought the north side down and facilitated the immediate demise of the south side after the chains ripped loose. A thorough inspection of the bridge had not been conducted for 16 years prior to the disaster and inspectors sometimes used binoculars to inspect the chains from the road deck.

Because the connection details of the Silver bridge suspension chains made it difficult, if not impossible, for such a crack to be detected, a twin bridge upriver was dismantled before it suffered the same fate. A more far-reaching immediate consequence was a new requirement that all bridges in USA be inspected according to federal guidelines. Many bridges throughout the country were closed or had speed limits and traffic loads imposed on them. The Silver bridge, which had been so vital to the life of the area, was replaced within two years by one of a cantilever design - the type that failed at Minneapolis.

In the decades since the collapse of the Silver bridge, there have been other sudden highway bridge failures, most notably the Mianus river bridge on Interstate 95 in Connecticut in 1983 and the Schoharie creek bridge carrying the New York thruway over its namesake stream in 1987. In both cases, lax inspection and maintenance procedures were found to be at fault.

The Mianus failure was traced to excessive corrosion that resulted when roadway drains were paved over and missing gutters were not replaced. At Schoharie, severe, undetected scour under one of the bridge piers led to its sudden collapse.

West Gate bridge, 1970

The West Gate bridge is a large cable stayed box girder bridge in Melbourne, Victoria, Australia. Two years into construction of the bridge, on October 15, 1970, the 112 m span between piers 10 and 11 collapsed and fell 50 m to the ground and water below. Thirty-five construction workers were killed. A Royal Commission was set up to investigate the failure of the West Gate bridge. The causes of this were much more complex and were primarily those of adoption of a new method of erection, design error (section width to wall thickness ratio was very high, wall thickness slenderness equivalent to an egg shell) and lack of communication between principal parties. These led to release of bolts in the top flange to permit alignment, to an extent that the flanges buckled. Completed in 1978 after 10 years of construction, the bridge, a part of the larger West Gate freeway, cost US$ 202 million.

Sunshine Skyway bridge in Tampa Bay, Florida, 1980

When the Sunshine Skyway bridge (steel cantilever bridge) was rammed by the wind-blown freighter Summit Venture on May 9, 1980, a 427 m chunk of concrete roadway crashed into the waters of Tampa Bay, taking seven vehicles and a bus with it. Thirty-five people died. This was replaced by the world's longest bridge with a cable stayed main span, with a length of 8.85 km in 1987.

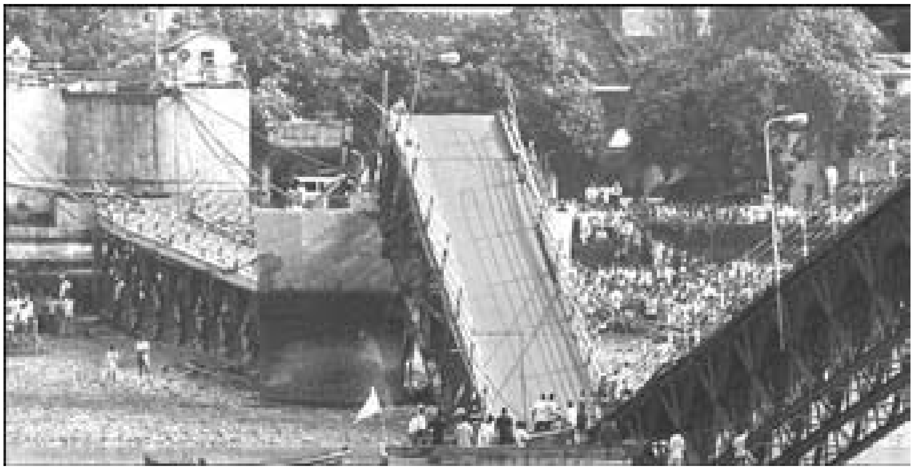

Figure 5. Bridge in Daman, India 2003

Bay bridge near Oakland, California, 1989

When a magnitude 7.1 earthquake rocked the San Francisco bay area in 1989, the Bay bridge came apart, sandwiching cars between the sections. The collapse of part of the Cypress freeway killed almost two-thirds of the 67 victims in the disaster.

Sungsoo Bride in Seoul, South Korea, 1994

The main span of Sungsoo bridge over Seoul's Han river (built in 1979) collapsed during the morning rush hour on October 21, 1994. The bridge collapsed when one of its concrete slabs fell due to a failure of the suspension structure, killing 32 commuters and injuring 17. This structural failure was caused by improper welding of the steel trusses of the suspension structure beneath the concrete slab roadway. The new bridge was reopened on July 3, 1997, after being redesigned and rebuilt.

Queen Isabella causeway in Port Isabella, Texas, 2001

A towboat captain lost control of a string of barges and strong currents sent the barges smashing into a 49 m section of the only bridge leading to the popular South Padre Island. Eight died after their vehicles plunged into the water 85 feet below.

Bridge in Lisbon, Portugal, 2001

A bus and two cars with at least 60 people inside plunged 50 m into the swollen Douro river after part of the bridge collapsed on March 5, 2001.

Interstate 40 bridge in Webbers Falls, Oklahoma, 2002

A vessel struck the bridge, collapsing a 152 m section of roadway onto a barge. More than a dozen vehicles were sent plunging into the water with people trapped inside, killing 14 on May 26, 2002.

Bridge in Daman, India 2003

The concrete bridge in the western coastal area of Daman, about 120 miles north of Mumbai, India, collapsed, sending a school van, two rickshaws and motorcycles plunging into the muddy river. At least 25 people, including 23 children, died. After the public outrage that followed, the bridge was rebuilt by the National Building Construction Corporation, a government body, at a cost of more than Rs. 10 crore. Barely one and a half

Figure 6. The San Francisco - Oakland Bay Bridge in Oakland, California, 2007

Figure 7. Jiujiang bridge in Foshan, China, 2007

months after its construction, the bridge collapsed again in August 2004 due to heavy floods!

Auto-route 19 bridge in Laval, Quebec, Canada, 2006

An overpass built in 1970, collapsed onto auto-route 19 in Laval, Quebec, on September 30, 2006. Five were killed in the collapse and six others were injured. Corrosion of the steel reinforcement bars inside the concrete as well as wear and tear were considered to be the cause of this collapse. The replacement overpass for Boulevard de la Concorde opened to traffic on June 13, 2007.

The San Francisco - Oakland bay bridge in Oakland, California, 2007

The San Francisco - Oakland bay bridge collapsed onto another highway ramp in Oakland, California, April 29, 2007, after a gasoline tanker truck overturned and caught fire.

Jiujiang bridge in Foshan, China, 2007

A boat hit the Jiujiang bridge in Foshan, in south China's Guangdong province, collapsing a 200 m section of the bridge and sending nine people into the Xijiang river on June 15, 2007.

Bridge in South Vietnam, 2007

A section of a bridge under construction in southern Vietnam collapsed on September, 26, 2007, killing at least 52 workers and injuring 97 others. The 1.7 mile bridge was started in 2004 and was expected to be finished in 2008. It was to be the largest suspension bridge in Vietnam. The bridge was being built across the Hau river, a branch of the Mekong River, in the southern city of Can Tho. It is part of a heavily used route linking the Mekong delta and Ho Chi Minh city. The collapsed section was more than 98 feet tall and was situated above land on the river bank in Vinh Long province. Concrete had been poured into the collapsed section just one day earlier. The bracing supporting it had apparently weakened and gave way.

Monitoring, inspection and costs involved

The Minneapolis bridge failure raise questions about bridge design as well as inspection systems. According to a six year old federal study, less than 4 percent of weld inspections correctly identify crack propagation. One potential solution is the use of piezoelectric sensors installed at potential failure points. Sensors could be wirelessly connected to monitors that would give advance warning of material or joint degradation. Meanwhile, there are scores of deck truss bridges throughout the U.S., triggering demands for immediate inspections. New York inspected all deck truss bridges soon after the failure of the Minneapolis bridge.

Figure 8. Bridge in South Vietnam, 2007

Figure 9. Artist's rendering of the proposed concrete bridge

Dozens of new technologies can help monitor bridges: X-ray machines that can spot hidden cracks in girders, computerised monitors that track minute changes in stresses on steel beams and sensors embedded in concrete that track corrosion of steel reinforcing beams. It may cost about US$ 250,000 to install a monitoring system on a large bridge.

Rengaswamy Srinivasan of LifeSpan Technologies, Atlanta (which sells bridge monitoring systems), who is directing the Applied Physics Laboratory work on concrete sensors, said one of the goals of his company is to create sensors that someday would cost less than US$ 10 each.

ASCE's report card says that between 2000 and 2003, the percentage of America's 590,750 bridges rated structurally deficient or functionally obsolete decreased slightly from 28.5% to 27.1%. However, it will cost US$ 9.4 billion a year for 20 years to eliminate all bridge deficiencies.

New I-35W bridge

The Minnesota state department of transportation (MnDOT) has chosen the most expensive bid to replace the collapsed interstate bridge. The winning bid from Flatiron and Manson Construction, at US$ 234 million, was the most expensive and may take the longest estimated time for completion among the competing designs (437 days - by Christmas eve 2008). The emergency response, site clean-up, stepped-up inspections of other spans, traffic diversions and new bridge could cost state and local governments US$ $ 393 million if incentives in the reconstruction contract are earned in full. Pile driving for the new bridge began on November 13, 2007[4].

This concrete box-girder bridge features twin 154 m central spans over the Mississippi river. It will have special LED lighting, railings that allow drivers to see the river and a sensor system to detect potential failure. Observation decks are planned on the river's edge at the base of the hourglass shaped 21.3 m piers. The bridge is also designed to allow for a pedestrian bridge to be suspended from the underside of the deck. It would connect parkland areas on either bank.

MnDOT representatives confirmed that Santiago Calatrava, the renowned Spanish architect, did try to offer a bridge design as part of the proposal submitted by the Walsh/American Bridge team. MnDOT's Kevin Western, a member of the six-person evaluation team, said the design was rejected because of a lack of redundant structural features.

Additional features of the new bridge

- Structural enhancements, including the use of high performance concrete to provide superior durability and multiple levels of structural redundancy to provide a long-lasting bridge for the future that will be economical to maintain.

- A state of the art sensor and monitoring system built into the bridge that will allow for easier and more comprehensive monitoring throughout the lifetime of the bridge.
- A comprehensive safety programme that will be implemented throughout all aspects of the design and construction process.

Acknowledgement

The material presented in the paper is based on numerous articles available on the internet. Some of the main articles are listed in the References.

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