XXV Konferencja Naukowo-Techniczna, Międzyzdroje 24-27 maja 2011
awarie budowlane 2011

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LEARNING FROM FAILURES AND MISTAKES – THEIR INFLUENCE ON U.S. BRIDGE CODES AND PRACTICE

NAUKA Z AWARII I BŁĘDÓW – ICH WPŁYW NA NORMY I MOSTOWNICTWO W USA

Abstract Engineers have been reacting to the lessons taught by natural forces, manmade loadings and socio-economic factors throughout history. This presentation looks at how failures caused by underestimating natural forces and material limitations have influenced bridges design specifications in the US, particularly the earlier AASHTO Standard Specifications [1] and the current AASHTO LRFD Bridge Design Specifications (2), as well as the knowledge base and the state of professional practice.

Streszczenie Inżynierowie uczą się z lekcji, które gotują nam przez wieki siły przyrody, obciążenia spowodowane działalnością człowieka, jak również czynniki społeczno-ekonomiczne. W referacie przedstawiono wpływ awarii spowodowanych niedocenieniem sił przyrody i właściwości materiałowych na normy do projektowania mostów w USA, a w szczególności AASHTO Standard Specifications [1] oraz obecną normę AASHTO LRFD Bridge Design Specifications [2], w odniesieniu do stanu wiedzy oraz praktyki projektowo-budowlanej.

1. Introduction

In discussing the subject of this paper, one of the first problems is to define exactly what is meant by a „failure”. The easy definition is that a failure is any unplanned consequence in construction or service. However, this all encompassing definition is too vague and requires some specificity. Of course, a collapse is an event that is relatively easy to identify and agree on. The cause of the collapse, however, is often something far more elusive. The inability to serve the intended function due to lack of sufficient strength or misalignment might also be considered a failure. Unsightly defects in a structure are sometimes also regarded as a failure and this may take the form of cracks, misalignments or discolorations. To the owner, a disproportionate future maintenance cost and/or a shortened service life might also be considered a failure to achieve all the goals.

The engineering profession reacts to failures with several common approaches. One of the first is to research the incident to determine the specifics of the cause, especially if it involves previously unknown or underappreciated phenomena. Once the subject is better understood, it’s a common approach to add additional provisions to our governing specifications for design and construction to avoid future repetitions of the event. Sometimes it is also necessary to change specifications for materials, fabrication or construction methods. Non-specification knowledge, which while not prescriptive in nature, nonetheless forms the information base about which bridge engineers are expected to be cognizant. Operational changes may be invoked in order to prevent other occurrences. Similarly, policy changes may also be invoked. Where other existing structures are found to be vulnerable to the underlying causes of this specific event, the existing structures may be strengthened or otherwise retrofitted to make them more robust and less vulnerable. On occasion, demolition of suspect bridges has also taken place. Of course, a mixture of all of these strategies may be used.

To further illustrate how the engineering profession has reacted to failures and near failures, consider the examples discussed herein.

2. Vessel Collisions

In 1980, the Motor Vessel Summit Venture hit a side span pier of one of the parallel cantilever trusses forming the Sunshine Skyway in Tampa Bay in the state of Florida with the result shown in Fig. 1. These particular piers were not protected from vessel collision. The response to this collapse, which resulted in numerous deaths, was a research project leading to the 1994 publication of a Guide Specification for Vessel Collision [3]. The principles in this document were incorporated into the First Edition of the AASHTO LRFD Bridge Design Specifications (AASHTO LRFD) in 1993. The design process has been updated and the specifications adjusted accordingly when the Guide Specification was republished in 2008. Various investigators contributed to expanding the knowledge base regarding vessel collision [4, 5].

Fig. 1.View of Skyway Collapse (Courtesy of Donald F. Sorgenfrei)

One of the underlying principles of the vessel collision design methodology is the calculation of the annual frequency of collapse of a bridge or component of a bridge which is taken as the product of several variables which reflect the annual number of vessels classified by size and shape passing under the bridge, the probability of vessel aberrancy, a geometric factor related to the probability of a collision between the aberrant vessel and a bridge pier or span, a factor to account for the probability of collapse due to the collision, and finally an adjustment factor to account for potential protection of piers from vessel collision due to upstream or downstream land masses or other structures that can block the vessel. The probability of aberrancy is considered as a product of several variables to reflect a base rate of aberrancy, a correction factor for the bridge location, a factor for current acting parallel to the vessel transit path, a correction factor for cross currents acting perpendicular to the vessel transit path and another factor related to the vessel traffic density. Criteria for all these factors are outlined in either the Guide Specification or the AASHTO LRFD.

Despite efforts to quantify the important parameters in the vessel collision scenario, it is very difficult to eliminate human factors and randomness.

Human factors and random events had a great deal to do with the vessel collision with the bridge near Webber Falls, Oklahoma, shown in Figs. 2, 3 and 4. In this particular incident, several barges and a tug boat appeared to be traveling in a transit line which was oriented towards going through the protected navigation span. It appears that the pilot lost control of the tug and it took the path shown by the dotted line in Fig. 2, resulting in collapse of a pier shown in Figs. 3 and 4. Several vehicles vaulted through the opening resulting in numerous deaths.

Among the factors at work in this particular incident where the following:

- The barge that impacted the pier column was reversed in its position such that the stronger stern hit the pier and exerted more load than if the barge had been properly positioned and the bow struck the pier.
- The impact involved the corner of the barge which had less energy absorption capability than if the impact had been with the frangible center of the barge.
- Finally, the collision involved the weakest pier in the structure.

Fig. 2. Apparent Path of Aberrant Barge Tow at Webber Falls (Source: Oklahoma DOT)

Fig. 3. Views of Damage at Webber Falls (Courtesy of Zolan Prucz)

In this case, the reaction to this event involved operational and policy recommendations for alarms on the controls of tugs to sense whether the controls had not been activated for a particular period of time which might indicate a medical incident involving the pilot. Additionally, dolphins comprised of large diameter, highly reinforced drill shafts were added to protect a number of piers of this and other bridges. Some of these dolphins are shown in Fig. 5.

Fig. 4. Views of Damage at Webber Falls (Courtesy of Zolan Prucz)

Fig. 5. Vessel Collision Retrofit (Courtesy of Jensen Construction Company)

3. Component Fracture

The Silver Bridge across the Ohio River collapsed in December of 1968 [6]. This collapse resulted from the fracture of an eyebar in an eyebar chain suspension bridge shown in Fig. 6. This was a seminal event in United States bridge engineering resulting in several different responses. A fracture control plan was implemented for fracture-critical members which related to the materials and the fracture toughness, the fabrication and welder qualifications and testing procedures, thorough documentation throughout the fabrication process, and careful documentation for weld repairs. The design specifications were altered to require the identification of fracture-critical members, i.e. components whose failure could be expected to result in partial or total collapse of the bridge, in the plan set. In some cases even tension components and structures which are not designated as fracture-critical must now be designated on the plans. Fracture toughness requirements were identified as a material requirement, but were not specifically integrated into the design specifications. From a policy point of view, this collapse resulted in the National Bridge Inspection Standards in the United States as outlined in Title 23 of the Code of Federal Regulations, Part (650 cc). This requires inspection of every bridge at intervals not greater than two years, and further special requirements for the inspection of components regarded as fracture-critical. Redundancy of structures was stressed in the design process and numerical, i.e. computer simulation, demonstrations of redundancy were permitted. In terms of retrofits of existing structures, a virtually identical eyebar suspension bridge was demolished and replaced. Other structures had redundancy added through the addition of auxiliary components.

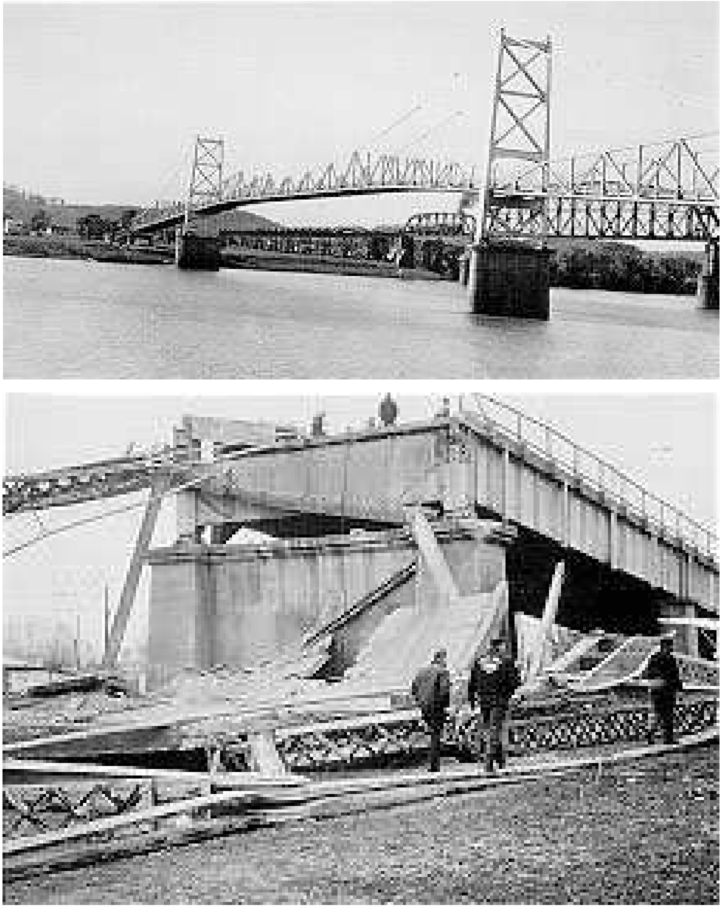

Fig. 6. Views of Silver Bridge Before and After Collapse (Courtesy of FHWA)

In December of 2000, several cracks were found in the girders of the Hoan Bridge in Milwaukee, Wisconsin, shown in Figs. 7 and 8. As can be seen in Fig. 8, several girders in the same span cracked virtually full-depth. All the fractures were brittle fractures initiating at intersecting welds. The problematic detail causing these fractures is shown in Fig. 9. It involved a series of intersecting welds which resulted in a triaxial stress state. No fatigue cracks were found associated with these problematic details. However, the shelf plate and the lack of a direct connection of the transverse stiffener created a large crack-like detail, which combined with the near inability of the steel to yield because of the intersecting welds, resulted in a scenario for brittle failure.

The response for this situation involved a memorandum from the Federal Highway Administration (FHWA) that sited two criteria that can indicate fracture vulnerability of this type. They were:

- Intersecting or overlapping welds
- The evidence of rapid crack growth

The body of knowledge was expanded through detailing guidance which involved elimination of the intersecting welds, usually by providing at least a 1/4” space between the welds, to allow for relief of constraint.

Fig. 7. General View of Hoan Bridge (Courtesy of FHWA)

Fig. 8. Close-up of Cracked Area (Courtesy of FHWA)

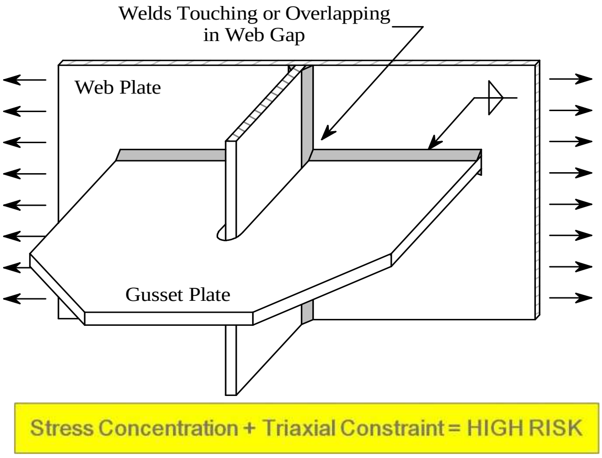

Fig. 9. Problematic Detail (Courtesy of FHWA)

4. Fatigue

Fig. 10 shows one of the early in-service fatigue failures in the United States at the Yellow Millpond Bridge. As a result of this and other instances of fatigue cracking, significant research projects were undertaken to characterize the response of various types of welded details. The result was an addition to design specifications requiring design on a stress range basis using SN curves for common welded details as shown in Fig. 11. Of course this deals only with the resistance side of the design equation, and studies were also undertaken to quantify the traffic side as well. These are commonly referred to as loadometer studies, and in more recent years weigh and motion studies (WIM). By in large, in United States practice, a relatively successful design specification has evolved for the treating of what is termed „load-induced fatigue”.

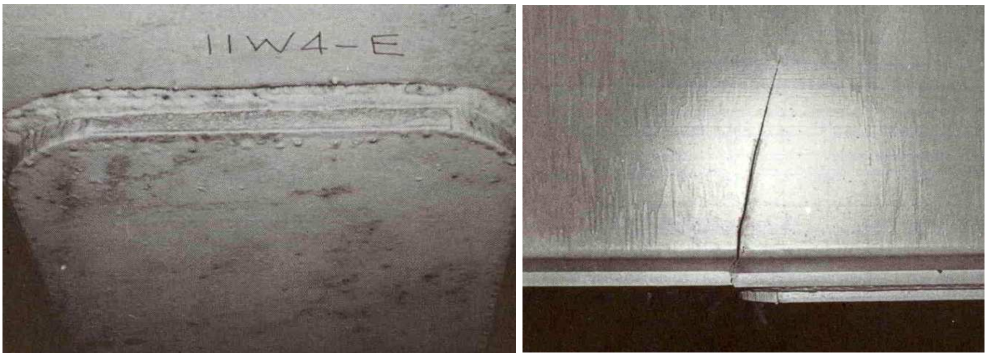

Fig. 10. Early Fatigue Crack on Yellow Millpond Bridge (Courtesy of John F. Fisher)

As a practical matter, much of the fatigue damage actually observed in the structures in the United States is related more to what is referred to as distortion-induced fatigue. A typical situation involving that type of response is shown in Fig. 12. This type of damage typically results from a small gap between structural components which is subject to a relatively small movement through the disconnected gap. In this scenario a relatively small displacement can result in a very large stress range. The response to this type of fatigue damage involved research to attempt to identify the important parameters and the development of a body of knowledge resulting from case studies subject to the research [7]. The specification changes have been limited to the identification of certain types of details which are no longer allowed in design of new structures in the United States. To-date there has been no robust quantification of this type of fatigue in the Design Specifications. Bridge inspectors are routinely trained to be aware of these types of cracks and how to identify suspect details.

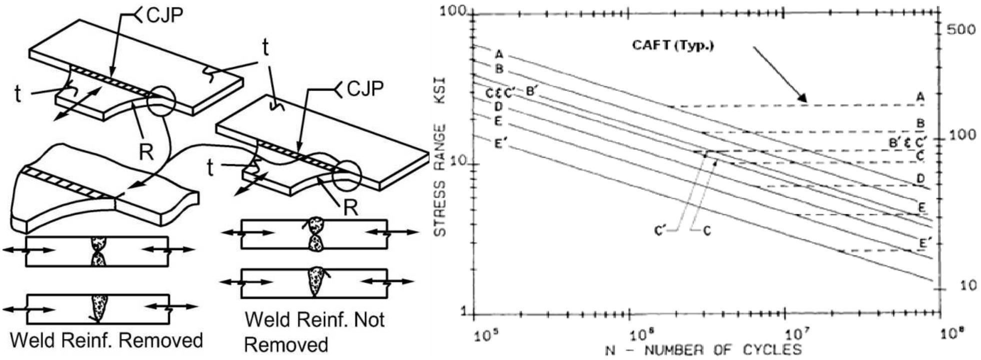

Fig. 11. Basis of Current Fatigue Design (Source: AASHTO LRFD)

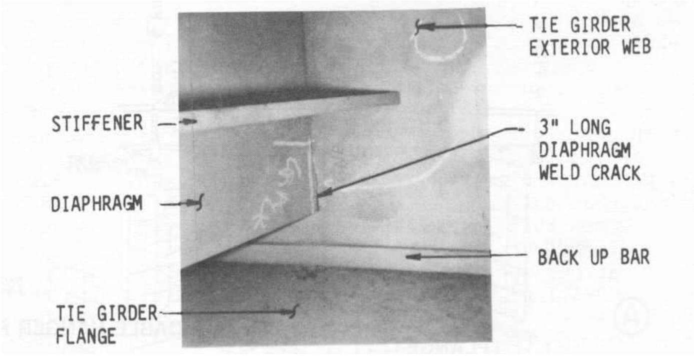

Fig. 12. Distortion-induced Fatigue Crack (Courtesy of John M. Kulicki)

5. Dynamic Wind Events

Fig. 13 shows one of the last stages in the collapse of the First Tacoma Narrows Bridge, a failure related to dynamic wind events. As a result of these types of failures, research proceeded to increase the understanding the dynamic response of more flexible structures. Design Specifications were modified to require static design pressures, and in the case of the United States specifications, an overturning line load applied to deck structures. The body of knowledge was expanded on several fronts including the identification of the basic factors involved in aerodynamic stability of structures and testing protocols involving section models, aeroelastic models, terrain models and now computational fluid mechanics-based methods. Fig. 14 shows the aeroelastic model of the Akashi-Kaikyo Bridge in a large wind tunnel in Japan. A variety of structural and dynamic retrofits have been instituted at various structures to either increase the stiffness, add damping or change the aerodynamic characteristics of the cross-section.

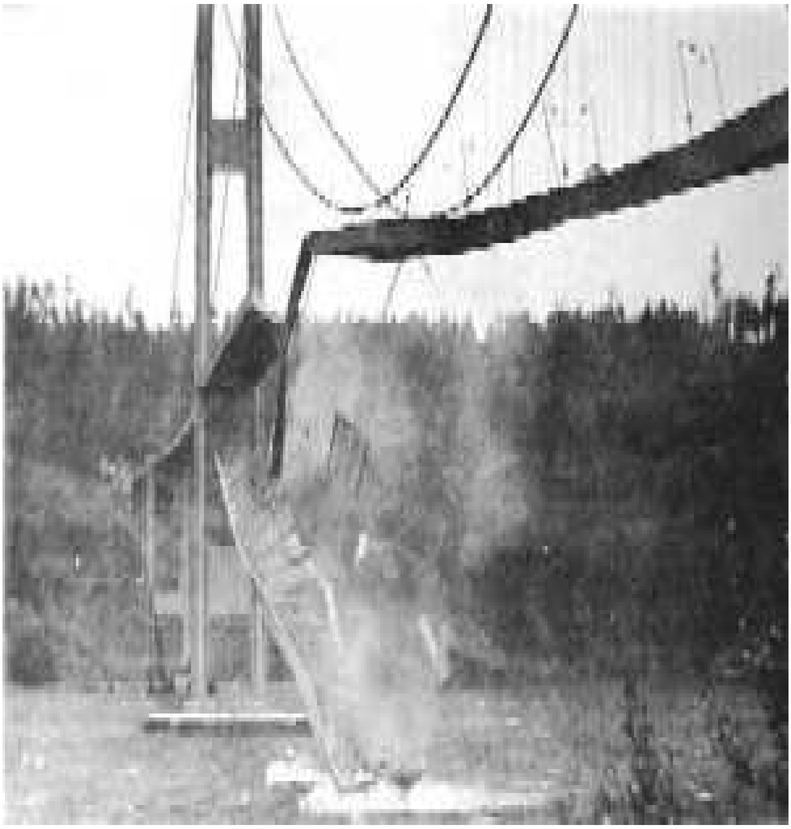

Fig. 13. Collapse of First Tacoma Narrows Bridge (Source: Britannica.com)

Fig. 14. Aeroelastic Model of Akashi-Kaikyo Bridge (Courtesy of John M. Kulicki)

The advent of the cable-stayed bridge has given rise to yet another wind dynamics issue often referred to as the wind/rain cable vibration. In this case the formation of rivulets of water are thought to be sufficient to change the aerodynamic characteristics of the cable cross-section to create large vibrations. There have been some instances where these vibrations have occurred in the absence of the rain further exasperating the search for solutions. Various methods have been used to control these motions, including energy absorbing pads between the cable ends and anchor pipes, cross-tying cables together, counter stayes to connect upper reaches of cables to the deck modifying the cable shape to change the aerodynamic characteristics and the installation of energy absorbers or dampers on the cables. One use of cable dampers in a retrofit scenario is shown in Fig. 15.

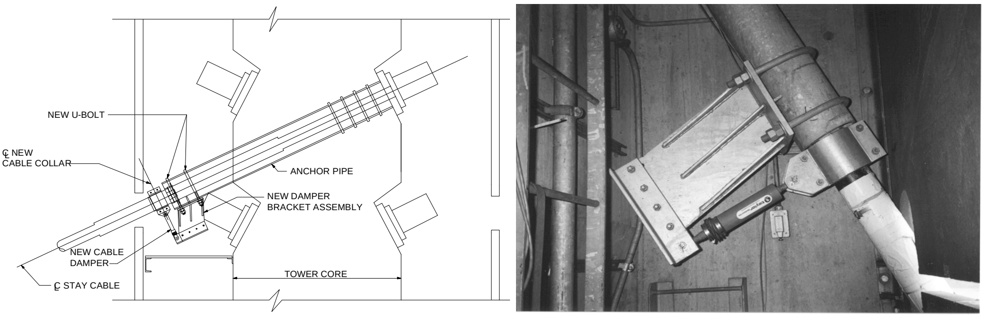

Fig. 15. Damper added to Eliminate Wind-Rain Vibrations (Courtesy of Modjeski and Masters)

6. Earthquake Damage

While earthquakes have been part of the natural environment in many parts of the world before the dawn of recorded history, in the United States the earthquake in San Fernando, California, in 1971 was a wake-up call to the design profession. Damage from that earthquake is shown in Figs. 16 and 17.

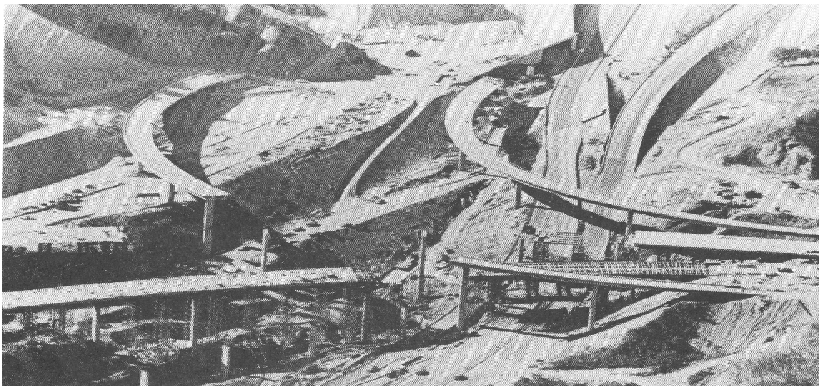

Fig. 16. Damage to Interchange from 1971 San Fernando Earthquake (Source: California DOT Photo Archives)

The response to this involved a great deal of research to understand this cyclic and hysteretic behavior of reinforced concrete components capitalizing on research previously done in the building industry through the National Earthquake Hazard Reduction Program (NEHRP) in conjunction with the Applied Technology Council. This was extended by another Applied Technology project (ATC 6) [8] which led to the development of the initial publication of a design process [9] which eventually became Division 1A of the AASHTO

Standard Specifications. These specifications included design spectrums, site factors that reflected the potential for magnification of motion in various types of soil or rock, as well as force reduction factors related to the ability of certain types of structures and details to undergo significant non-linear response to absorb the seismic energy. Methods of analysis were specified as were seat widths intended to prevent the dislodging of structures. The specification highlighted the requirements for confinement of reinforced concrete as a means of increasing ductility, and plastic hinging as a way of absorbing energy and limiting the force that foundations were required to withstand. Based on the observations from the San Fernando earthquake, bond and development length requirements were changed in the seismic areas to reflect the importance of this behavior.

Earthquakes continued to occur and additional lessons were learned. Significant damage was done to structures in the Northridge area by an earthquake which occurred in 1994. Some of the damage inflicted by that earthquake is shown in Figs. 18 and 19. On the positive side, the apparent good behavior of some of the retrofits to structures in California as a result of the earlier earthquakes, including column wrapping, longitudinal restrainers and base isolation, was noted.

Fig. 17. Typical Column Damage from 1971 San Fernando Earthquake (Source: California DOT Photo Archives)

Improvements to the Seismic Specifications have continued over time and in 2007 AASHTO upgraded the seismic design required in the LRFD Specifications to include the design for 1,000 year return period event, as well as new hazard maps for peak grout acceleration and peak horizontal spectral response acceleration coefficients. A new method of constructing the response spectrum for a given site was instituted as were revised site factors, further requirements for P-Δ effects and new provisions for columns and foundations. Additionally, in that same year, AASHTO adopted a Guide Specification for displacement-based seismic design [10] as a parallel to the force-based specification contained in the AASHTO LRFD. Designers in the more seismic areas now have a choice of either of these specifications to utilize.

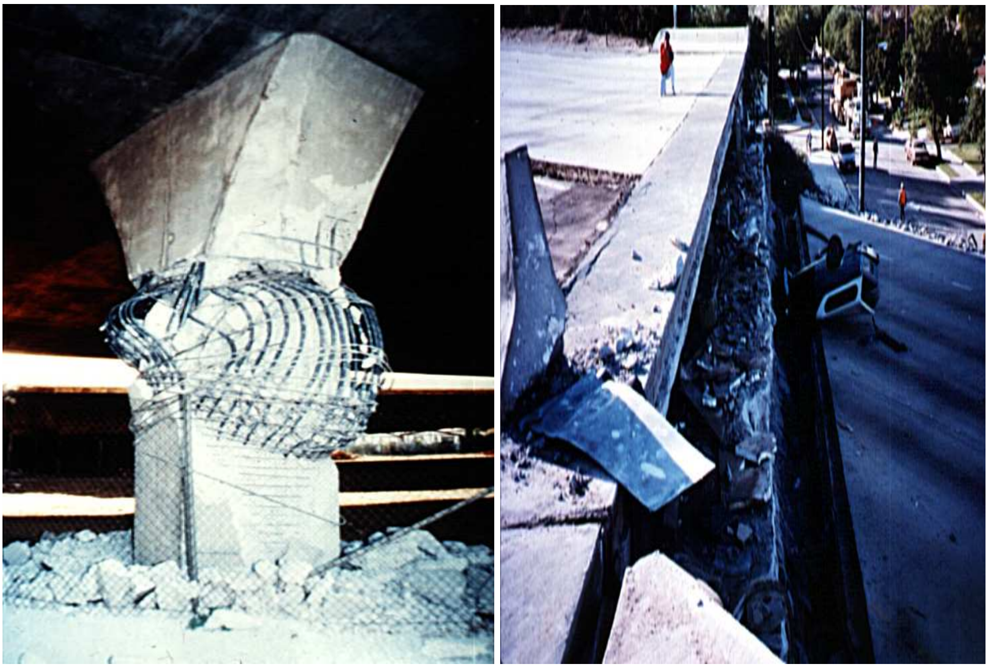

Fig. 18. Damage from 1994 Northridge Earthquake (Source: University of Buffalo/MCEER Photo Archives)

Fig. 19. Damage from 1994 Northridge Earthquake (Source: University of Buffalo/MCEER Photo Archives)

7. Forces from Coastal Storms

In 2004 and 2005, three hurricanes ravaged the Gulf Coast area of the United States. Several relatively long bridges crossing bays in the coastal areas were destroyed resulting in a replacement cost of over a billion dollars. Typical damage is shown in Fig. 20. In response to this, the Federal Highway Administration initiated a research project to develop a specification to provide design guidance for the forces encountered in these events [11, 12]. It was believed that the destruction of many spans of prestressed concrete beam bridges resulted from a combination of buoyancy and wave-induced forces. Interestingly, similar phenomena and bridge damage were discussed almost 25 years earlier [13]. A research team consisting of structural engineers and ocean engineers developed a process for calculating the wave forces using relevant meteorological and oceanographic data pertaining to an individual site, based on numerical simulations supported by wave tank studies. A typical experimental response is shown in Fig. 21. This work lead to the adoption by AASHTO of a document entitled „Guide Specifications for Bridges Vulnerable to Coastal Storms" [14]. A parallel document on retrofit of existing bridges was also developed, but the magnitude of forces developed in coastal storms make retrofits very difficult and often impractical. Research into wave forces continues and further evolution of these specifications is expected. However, the relatively few instances since 2005 where significant storms have made landfall on the coastal United States has resulted in very little damage since these guide specifications were developed.

Fig. 20. Dislodge Spans of US 90 Bridge over Bay St. Louis, Mississippi, Resulting from Hurricane Katrina 2005 (Courtesy of Mississippi DOT)

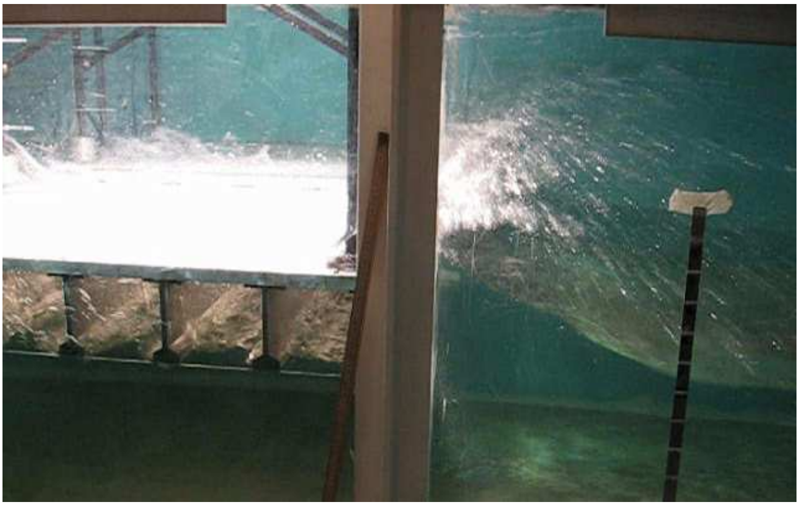

Fig. 21. Wave Tank Studies (Courtesy of John M. Kulicki)

8. Collapse of the I-35 Bridge across the Mississippi in Minneapolis, Minnesota

On August 1, 2007, the I-35 structure, which consisted primarily of a multi-span deck truss, collapsed into the Mississippi with a resulting loss of life. An aerial view is shown in Fig. 22. The response to this incident involved extensive investigations into the probable cause [15]. All deck trusses on major roads throughout the United States were reinspected. Particular emphasis was placed on gusset plates as it was quickly realized that the most probable culprit in this event involved a gusset plate which was found to be undersize, combined with certain events of the life of the bridge which increased the loads on the structure and an ongoing redecking operation which may have added additional temporary loads. Initial guidance on the analysis of gusset plates was produced by the FHWA [16] and many states have evaluated existing truss gusset plates using this process. Gusset plates have been strengthened and in some cases rivets have been replaced with high strength bolts to increase shear capacity. Simultaneously, a research project was initiated to characterize the behavior of gusset plates through a combination of sophisticated non-linear finite element analysis and testing of relatively large scale gusset plates. The considerably approximate nature of typical design procedures for gusset plates have been known for decades [17] and the current research program is further quantifying this difference between assumed and actual behavior and is expected to yield revised design specifications based on a much improved understanding of the distribution of stresses in these critical components, improved design methods, and resistance models. As of this writing, the work is still in progress and no codification of results have yet been achieved.

Fig. 22. Aerial View of Collapsed I-35 W Bridge, Minneapolis, Minnesota (Courtesy of FHWA)

9. Conclusions

As can be seen from the discussions of failures above, the profession has been in a continual process of observing an event, instituting research to learn about the causative factors and then instituting some application-oriented approach to trying to prevent subsequent repetitions of the same situation. Unfortunately, in the case of many of the natural phenomena, this has been a repetitive cycle as the profession learns from yet another instance of the same phenomena. The response to seismic design, in particular, has been replete with examples of learning from an event, codifying the results, bringing it into practice only to have the next event show the profession new lessons to be learned. The response to coastal and seismic issues demonstrates that society and, therefore, the design profession, in the United States, and probably other countries as well, often has an interest level which is inversely proportional to the length of time since the last major event.

So far, nature has been asking the questions and the engineering profession has been trying to find the answers. It begs the question as to whether a more proactive response is possible to identify fundamental responses and address them before they become catastrophes. Obviously, this is very difficult but maybe the engineering profession needs to take some actions to try to get ahead of the curve. The efforts now underway to try to assess the effect of future global climate changes on bridges, particularly bridges in the more vulnerable coastal areas may offer some guidance on how to approach the problem. Perhaps what we need is a workshop to explore other scenarios. This might involve collecting some high level innovative thinkers, people from other disciplines besides bridge engineering, and allow them to meet several times and consider what we might be missing. The objective would be to try and identify the next „big thing” to impact bridge engineering and start a plan of action to address it.

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Acknowledgements

Many of the photographs and figures contained in this paper have been generously contributed by professional colleagues. These include: Dr. John W. Fisher of Lehigh University, Dr. Dennis R. Mertz of The University of Delaware, Dr. Robert Connor of Purdue University, Mr. Jerry O'Connor of the Multi-Disciplinary Center for Earthquake Engineering Research at the University of Buffalo, Mr. David M. Barrett of Modjeski and Masters, and Dr. Zolan Prucz of Modjeski and Masters. The manuscript was prepared by Ms. Diane M. Long of Modjeski and Masters. Review by Dr. Thomas P. Murphy of Modjeski and Masters is also appreciated.