Resilient Bridge Design

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ABSTRACT

Bridge failure can result in the disruption of commerce and services, significant repair costs, and most importantly the loss of human life. Bridges rarely experience complete failure during non-extreme events. However, when such failures do occur, the results can be catastrophic. Lessons from past bridge failures can be applied for improving the resilience of bridge design and avoiding bridge failures. The framework presented in this paper illustrates the use of a fault-tree analysis to systematically determine contributing factors or events that could lead to a bridge failure. Once the factors are identified, the designers can address these factors in design for improving resilience and preventing failures. Examples on the use of fault-tree analysis are shown for steel and concrete bridges and substructure.

Introduction

This paper presents the essence of the FHWA publication titled Framework for Improving Resilience of Bridge Design, Publication No. FHWA-IF-22-016 (*Framework*). It provides an introduction to the *Framework* (Chavel and Yadlosky 2011), while also highlighting the fault-tree methodology through illustrative examples, and present the lessons learned from past bridge failures. The illustrative examples provide the tools for identifying potential failure modes and give suggestions for giving due considerations in the design to prevent such potential failures and to improve the resilience of bridge design. The *Framework* is expected to be of interest to students and instructors of bridge engineering, bridge owners, bridge designers, inspectors, fabricators, contractors, and maintenance personnel. A copy of the Framework may be downloaded from http://www.fhwa.dot.gov/bridge/pubs/hif11016/hif11016.pdf.

Definition Of Failure

Failure in this paper is defined as the inability of a bridge or one of its primary load-carrying components to no longer perform its intended function. For bridges under construction or in service, this framework considers the term failure in two different contexts: 1) collapse and 2) critical defect. A bridge collapse is the failure of all or a substantial part of the bridge where full or partial replacement may be required. The term critical defect refers to a condition in which the structure has undergone some deformation, section loss, or similar undesirable condition, but has not collapsed and can be repaired or retrofitted. Additionally, delays during construction and/or fabrication can be considered as a critical defect in the overall bridge construction process.

Failures can be caused by one, or a combination of errors in design, detailing, or construction; unanticipated effects of stress concentrations; lack of proper maintenance; overloads; the use of improper materials or foundation type; or the inadequate consideration of an extreme event. It has been shown through various studies (Wardhana and Hadipriono 2003, Lwin 2010) that a bridge failure is most likely to be caused by an extreme event, with the most prevalent type being flooding and scour.

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Throughout the *Framework*, examples of bridge failures and critical defects are provided. The use of failures and critical defects are not used to assign fault, but are to be used to learn the lessons of the past, and applied by designers to make new and existing bridges more resilient.

Design Omissions And Errors

The *Framework* does not necessarily consider the effects of an incorrect design for each specific bridge type, since design omissions and errors can occur in many places during the design process. A well established QC/QA program can help to avoid omissions and errors.

Quality Control And Quality Assurance Programs

Quality Control/Quality Assurance (QC/QA) programs are formal office or organizational procedures or practices for ensuring that the owner's requirements and expectations are fully met. A QC/QA program provides checks and balances within an organization to assure quality in the final products. QC/QA programs are implemented at different levels or phases of work activities. For example, in the design phase, the bridge designer is responsible for making sure his/her calculations and drawings are accurate and meeting the requirements of the design. The bridge designer is performing QC of his/her own work by establishing a procedure for self-checking the work for accuracy and correctness. On the other hand, the reviewer, practicing QA, is responsible for independently checking the work of the bridge designer to assure accuracy and correctness in meeting the design requirements and expectations of the bridge designer. In construction, QC is the responsibility of the contractor to ensure that the quality of the work is carried out in compliance with the contract provisions. On the other hand, the owner is responsible for practicing QA to assure that the contractor is carrying out the work in accordance with the contract.

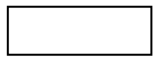
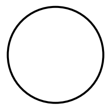
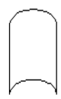
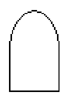
A good QC/QA program (Lwin 2010) is a deliberate and systematic approach to reduce the risk of introducing omissions and errors into a design. The likelihood of a failure in any design process is increased if standardized procedures are not established and followed. In some cases, the root cause of a bridge failure can be traced back to a failure to create or follow a good QC/QA program. The implementation and adherence to a good QC/QA program will likely reduce the possibility of failure of the over bridge design process.

For major bridge projects involving unusual, complex, and/or innovative features, a peer review may be desirable to raise the level of confidence in the quality of design and construction. A peer review is generally a high-level review by a special panel of experienced engineers specifically appointed by the Bridge Owner to meet the needs of the project. Peer review is an effective way to improve quality and to reduce the risk of omissions and errors.

Fault-Tree Diagrams

A fault-tree diagram is a graphic model that shows parallel and sequential failure paths that can lead to an undesirable outcome: in this case a bridge failure. A fault-tree diagram is helpful in determining potential failure modes and their interactions in a complex system, such as a bridge.

Table 1: Typical Fault Tree Diagram Symbols

Symbol	**Usage**	**Description**
	Events	Represents the Top Event and the Intermediate Events in the fault tree.
	Basic Event	Represents the Basic Event in the fault tree. Will be the lowest level of resolution in the tree.
	Or Gate	The output event associated with this OR gate exists if at least one of the input events (preceding event) exists.
	And Gate	The output event associated with this AND gate exists if only all of the connected input events (preceding events) exist simultaneously.

A fault-tree diagram is developed in a top-down direction. In this application the top event is the failure of the bridge. The events immediately beneath the top event lead to the execution of the top event. Successor events and conditions that most directly lead to the predecessor events are then determined. This process is repeated at each successive level of the fault-tree until the diagram is complete. Table 1 provides an explanation of the symbols typically used in fault-tree diagrams. Specific information regarding the use of fault-trees in engineering type applications can be found in Haasl et al. (1981).

Utilizing a fault-tree diagram, a bridge is modeled to demonstrate/determine the critical failure paths. The fault tree diagram illustrates the structural component interactions, redundancy, actions/causes such as corrosion or fatigue, and environmental impacts such as flooding or scour. The failure paths depicted in the fault-tree diagrams are intended to provide bridge designers with a means to improve bridge designs and prevent future failures. If bridge designers understand critical failure modes related to the particular bridge being designed, they may be able to employ additional analyses or design calculations to investigate potential failures and determine strategies to assess and rectify issues not typically addressed during the design phase.

The general fault-trees presented in this paper are qualitative; however these fault trees can be used in a quantitative sense as well. The vulnerability of a bridge can be determined by a numerical evaluation that employs the probability values of each basic event. Once the probabilities of the basic events are determined, Boolean algebra can be performed. This will result in the probability of failure of the top event - in this case, a bridge failure, and the relative importance ranking of each path of the fault-tree. LeBeau and Wadia-Fascetti (2007) discuss the use of Boolean algebra to determine the probability of failure of different failure path mechanisms for the collapse of the Schoharie Creek Bridge. Similarly, Daniels et al. (1991) perform a quantitative vulnerability assessment of several steel bridges, employing a method analogous to a fault-tree analysis. Both of these studies show that fault-trees have both qualitative and quantitative advantages that could be employed by a bridge designer during the design process.

Failure Framework For Typical Girder Bridges

The top categories of a general fault tree for a typical steel or prestressed concrete girder bridge are shown in Figure 1. Due to the size of the fault-trees and paper space limitations, the fault-trees are broken into smaller portions that fit this paper. As discussed previously, failure refers to a total collapse of the bridge system or an event that renders the bridge unfit for service.

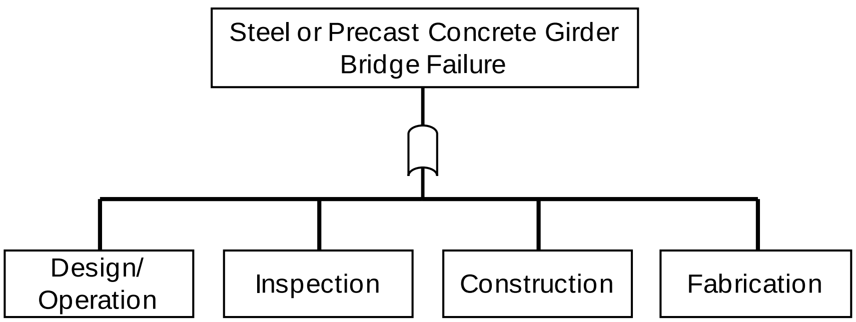


Figure 1: Top Categories of a Typical Girder Fault-Tree

In general, a fault-tree tends to be project specific, such as the case of the fault-tree developed by LeBeau and Wadia-Fascetti (2007) for the collapse of the Schoharie Creek Bridge. However, for this *framework*, in an attempt to include all girder bridges, I-, T- and box-girders, the fault-trees presented are shown for a general case.

The fault tree is established with the top event, the Steel or Prestressed Concrete Girder Bridge Failure, as shown in Figure 1. The failure can develop from four different categories; Design/Operation, Inspection, Construction, or Fabrication. These four categories are joined by an OR gate, which means any one of the four conditions can result in a failure. A bridge specific fault-tree will be more refined than the general cases provided herein. Also, not all of the aforementioned conditions will necessarily apply to the specific bridge in question, but the designer should be aware of all of the possible events in the fault-tree. For example, there will be some construction and erection aspects that don't necessarily fall under the bridge designer's control, but more so for an engineer working for a contractor, fabricator, or steel erector. These aspects are presented here so bridge designers understand and take into account the entire process of design, fabrication, construction, and inspection of the bridge.

The Design/Operation category alludes to the fact that a failure, either a collapse or a critical defect, can occur while the bridge is in service. Inspection refers to the fact there may be a problem with the regular inspection resulting from a design that does not facilitate inspection of the bridge components. The Inspection category does not intend to encompass problems with the actual bridge inspection, but highlight issues that can be addressed during design that will facilitate bridge inspection. A failure of the bridge process can occur during the Construction of the bridge, whether it is a collapse or a problem that results in delays. The Fabrication process is also subject to errors and problems, which could result in a failure of the bridge process. These are all conditions that the bridge designer should be aware of, and give due consideration to, when designing a girder structure. Each of the four categories can be developed into a more detailed fault- tree. The Design/Operation category is presented in the next section.

Steel Girder Bridge: Design/Operation Category

The fault-tree for the Design/Operation category for a steel girder bridge is shown in Figure 2. While in service, a bridge failure can result from either a failure of the superstructure or substructure, however, Figure 2 is dedicated to the superstructure only. A failure of the steel girder superstructure can be caused by a failure in any one of the superstructure components; the most severe are those occurring in the girders, cross frames or diaphragms (particularly in curved girder bridges), bearings, or concrete deck. An OR gate is used to join these fault scenarios, meaning that a failure of anyone of these components will cause a failure of the superstructure. A failure of the superstructure will then trigger a design/operational failure of the bridge.

Corrosion: Inadequate Drainage

For example, consider the Corrosion and Inadequate Drainage events shown in Figure 2. Inappropriately detailed drainage components can often become clogged and not provide for the removal of water and deicing salts from the structure. Thus, deterioration (corrosion) caused by the combination of water and deicing salts can cause the failure, in this case a critical defect, of the main bridge girders.

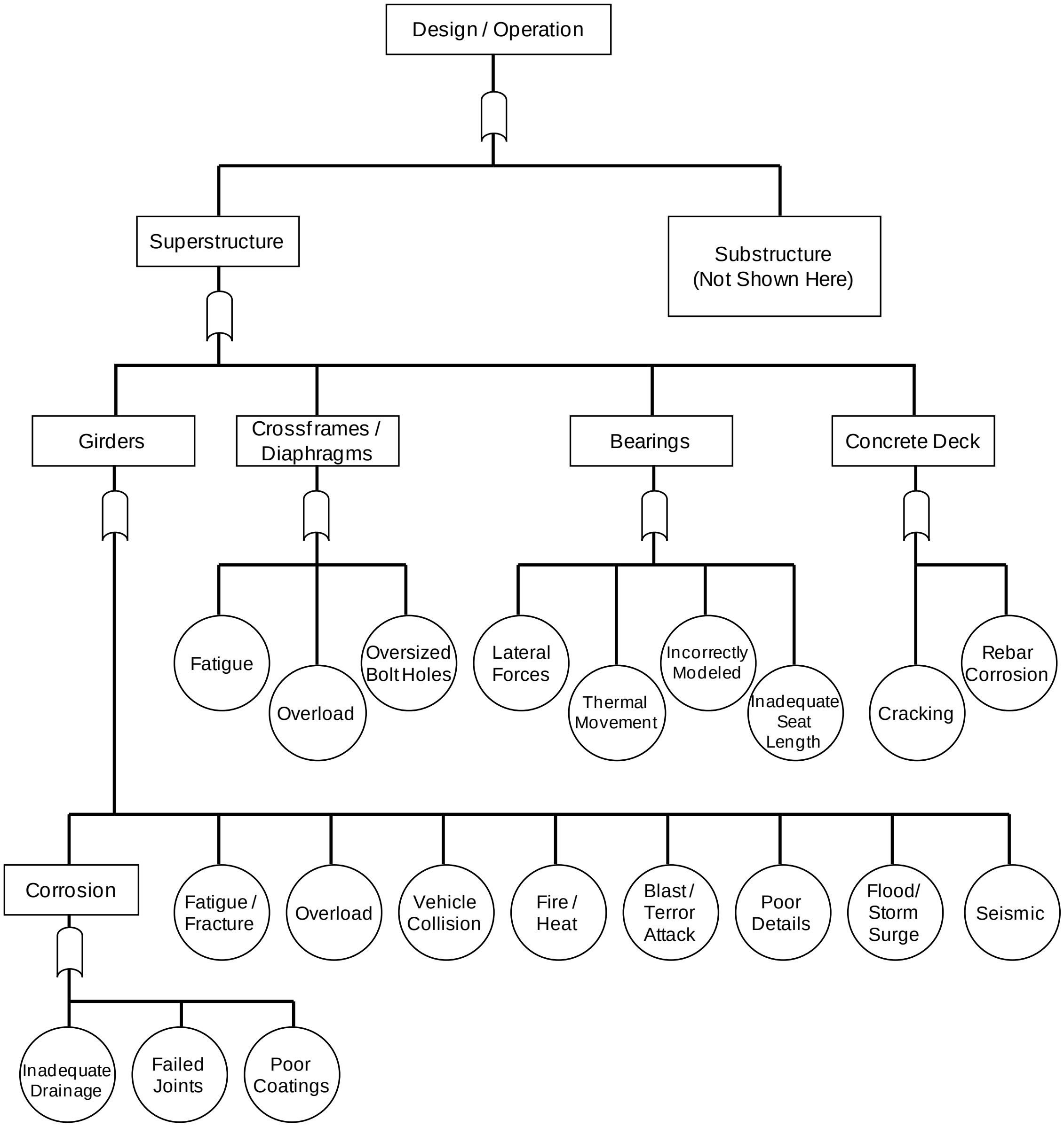


Figure 2: Portion of Steel Girder Bridge Fault Tree Showing Design/Operation Category

It is important to locate drainage scuppers and connecting elements in regions of the superstructure where, if they become clogged with debris, they will cause the least damage. It is also important that the down-spouting be accessible for inspection, maintenance, and repair, and has the necessary slopes and connections to prevent clogging.

In addition, it may be advantageous to make the steel superstructure continuous and eliminate expansion joints, thus eliminating drainage details that cause problems. An example of where simple spans are made continuous during a rehabilitation project, to eliminate poor drainage details is shown in Figure 3. Adequate drainage and the layout of the drainage elements will help to prevent girder corrosion, and subsequent failures or critical defects.

a) Before Rehabilitation b) After Rehabilitation

Figure 3: Elimination of Trough-type Drainage Details During a Rehabilitation Project

Fatigue and Fracture

There have been several reported steel girder bridge failures caused by either fatigue or fracture of the girder steel. A significant amount of research has been performed regarding fatigue over the past 50 years. The research has led to the categorization of various bridge details in the current design specifications that can be used by the bridge designer to investigate fatigue in the design process. The *AASHTO LRFD Bridge Design Specifications* (2010) has separated fatigue into two categories: load induced fatigue and distortion induced fatigue. In general, when provisions concerning fatigue sensitive details are followed, the potential failure of a bridge due to fatigue is significantly reduced.

Distortion-induced fatigue is addressed in the current specifications, but not in as much detail as load-induced fatigue. Distortion-induced fatigue crack growth generally results from small deformations, usually out-of-plane, in localized areas, and may not be readily apparent during the design process. Fisher et al. (1998) provide several examples of details that can be susceptible to distortion-induced fatigue:

- Rotation of floorbeam attached to main girder web
- Web gaps in multi-girder bridges at the diaphragm connections
- Lateral bracing connections.

Distortion-induced fatigue details should be given consideration by bridge designers. For additional information regarding fatigue, other than the current specifications, several references are provided in the *Framework* (Chavel and Yadlosky 2011).

Bearings

Bearing failure is a critical defect that could lead to collapse or partial collapse of a bridge. For example, rocker bearings can be susceptible to failure resulting from what is known as “ratcheting.” Debris and/or corrosion material can build-up on the rocker seat area and can prevent the bearing from moving freely as intended by design, thus imparting longitudinal forces into the support structure. The build-up of material, coupled with the movements caused by thermal cycles can result in the "ratcheting" effect of a rocker bearing.

On July 27, 2005, in Albany, New York, two adjacent steel I-girder spans of a multi simple-span girder structure fell off their support bearings at a pier supporting the expansion ends of two different two-span units (see Figure 4). The authors of the forensic investigation indicated that the failure could most likely be attributed to the fact that the bearings became overextended, due to their inability to return toward vertical during time of expansion of the adjacent span, thus pushing the pier to accommodate expansion (NYSDOT 2005). The bearings could not return to vertical due to a build-up of material over time. During periods of span contraction, the bearings could tip further, becoming more overextended, and repeated thermal cycles would cause the bearings to "ratchet" further, until they became unstable.

Figure 4: Rocker Bearing Failure (NYSDOT 2005)

<u>Precast Concrete Girder Bridge: Design/Operation Category</u>

The fault-tree for the Design/Operation category for a precast (prestressed or post-tensioned) concrete girder bridge is shown in Figure 5. It can be noted that the framework for a precast concrete girder bridges is similar to a steel girder bridge, with some minor differences.

A failure of a concrete girder superstructure can be caused by a failure in any one of the superstructure components, but mainly the girders, bearings, or concrete deck. Again, an OR gate is used to join these fault scenarios, meaning that a failure of any one of these components may cause a failure of the superstructure. A failure of the superstructure will then trigger an operational failure of the bridge. For example, poor reinforcement and/or duct detailing, too much water in the concrete mixture, or corrosive constituents can cause an operational failure of a concrete girder bridge.

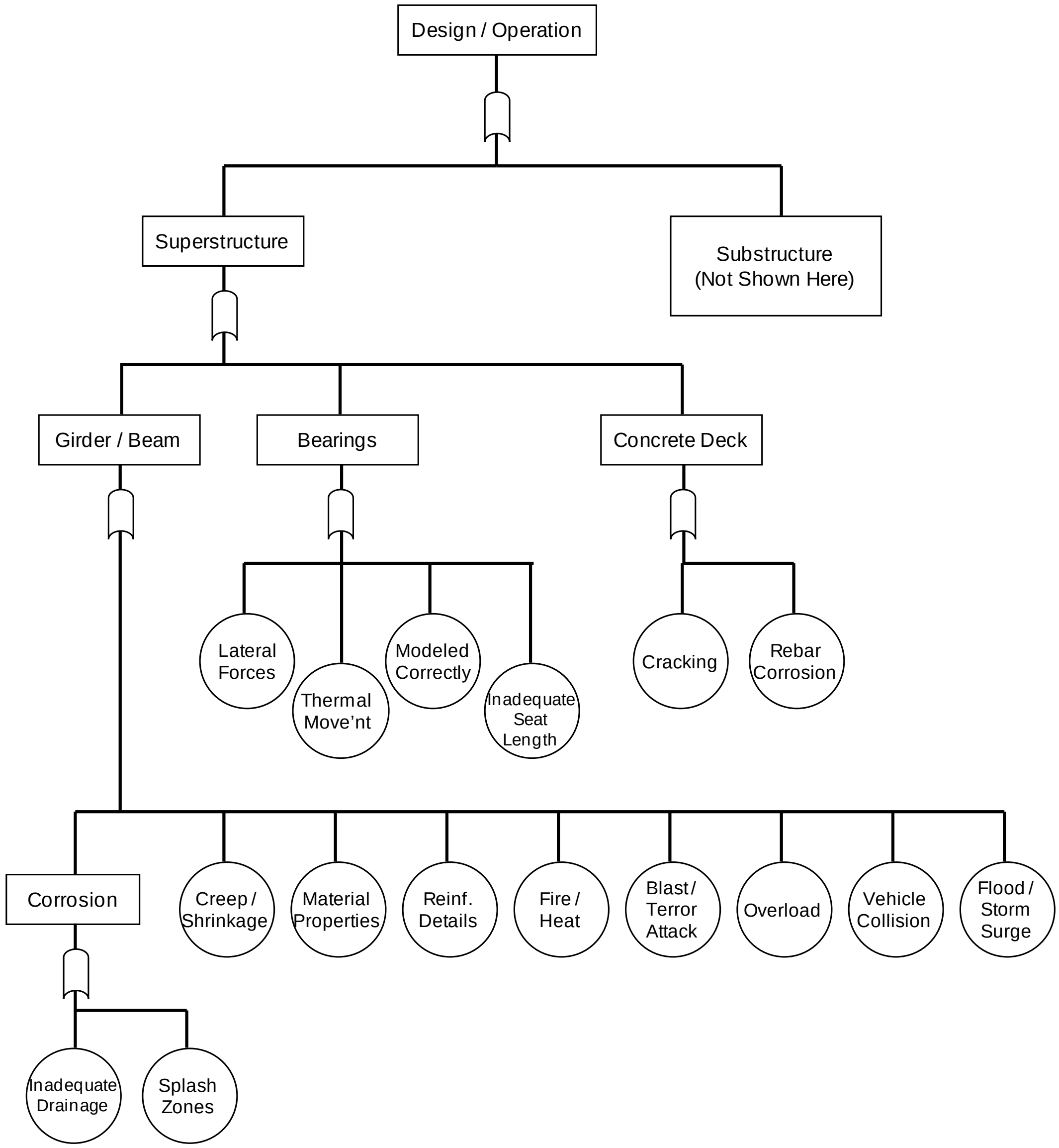


Figure 5: Portion of Precast Concrete Girder Bridge Fault-Tree Showing Design/Operation Category

Flood/Storm Surge

A bridge with a small vertical clearance over a waterway could be vulnerable to damage from a debris flow and storm surge in a flood. If the vertical clearance is small, it is possible that the girders of the structure will cause flood debris to be stopped at the bridge. This debris stoppage and water flow could lead to additional lateral loads on the steel girders that were unanticipated during design.

In August 2005, several concrete girder bridges were damaged or completely destroyed in Alabama, Louisiana, and Mississippi during Hurricane Katrina. Padget et al. (2008), used data from 44 damaged bridges to develop relationships between storm surge elevation, damage level, and repair costs. The authors point out that several traditional fixed spans displaced due to a combination of buoyant forces and pounding by waves. The US-90 Biloxi-Ocean Springs Bridge suffered severe damage due to a combination of storm surge and wind/wave induced loading (Padget et al. 2008). The four-lane, 1.9 mile, multi-span concrete girder bridge had low-lying spans. The storm surge caused severe damage to the bearings, and most connections between the deck and the pier caps were destroyed, allowing free movement of the spans. In fact, several spans on the western half of the bridge became completely unseated and were submerged in the bay, as shown in Figure 6.

Figure 6: Spans completely Unseated Due to Storm Surge Induced Loading (Padget et al. 2008)

In traditional hurricane prone areas, the designer may need to take measures to reduce the likelihood of failure caused by storm surge: the bridge could be designed to a higher elevation, provide details such as transverse shear keys to prevent lateral movement, or tie downs to prevent upward movement.

Fire/Extreme Heat

A fire or extreme heat event will cause high thermal gradients in a concrete girder, and as a result the surface layers of the concrete girder could expand and eventually spall off the cooler, interior portion of the girder. During an extreme heat event, when temperatures approach 800 - 1200°F, there can be a significant loss of strength in a concrete girder. The temperature, at which a concrete beam will fail, is mainly dependent upon the type of aggregate used. Concretes made with carbonate aggregates, such as limestone of dolomite, are relatively unaffected by temperature until they reach 1200°F to 1300°F, at which time they rapidly lose strength. Aggregates such as quartzite, granite, and sandstones undergo plastic change at about 800°F to 1000°F, which causes a sudden change in volume and spalling of the concrete. Lightweight aggregates gradually lose their strength at temperatures above 1200°F (MacGregor 1997).

On July 12, 2005, a significant fire incident occurred near Ridgefield, Connecticut which caused significant damage to an adjacent box-beam bridge. The Connecticut DOT coordinated with the FHWA’s Turner Fairbank Research Center to investigate the flexural capacity of the beams removed from the bridge after the fire. The results of the investigation showed that the beams still had sufficient flexural capacity but the long-term viability of the beams was questionable. The visual and petrographic examinations showed that the damage to the bottom flange concrete was sufficient to allow pathways through the concrete to the depth of the bottom prestressing stands (Graybeal 2007). This could potentially lead to the accelerated deterioration of the bottom row of strands due to water ingress and subsequent corrosion.

Bridge designers should be aware of the fact that a fire can occur below a concrete girder superstructure. Depending on the importance of the structure, it may be necessary to investigate the bridge behavior due to an extreme heat event to ensure that a collapse does not happen. A design could possibly be developed that would allow some delay before a collapse would occur.

Substructure

A general fault-tree for the case of a bridge substructure failure is shown in Figure 7. As shown in the general fault-tree, several causes of substructure failure are related to extreme events, such as scour due to flooding, vessel collisions, and earthquake loading.

Vessel Collisions

Bridge designers must consider the lateral loads imparted to bridge piers by ships and/or barges when the structure being designed crosses a navigable waterway. Similarly, for an overpass structure, lateral loads resulting from vehicle or train collisions must be considered when bridge piers are located near traffic lanes or a railroad below. Collisions with bridge piers by barges/ships, trains, or vehicles that cause a bridge to fail can not only result in the loss of human life, but will damage the transportation system and economy, especially for failures occurring on major thoroughfares. Wardhana and Hadipriono (2003) note that 59 bridge failures, or 12% of the total number of bridge failures studied, resulted from land and marine vehicle collisions.

There have been several reported incidents of piers weakened or destroyed by vessel or vehicle collisions, subsequently causing a bridge failure. One such incident occurred on May 26, 2002, in which a towboat with two barges collided with a pier of the I-40 Bridge in Webbers Falls, Oklahoma, killing 14 people and injuring several others (NTSB 2004). The traffic in both directions of the major east-west national corridor was abruptly stopped. Reinforced concrete piers utilized spread footings and pier protection was constructed only on the upstream side of the main span, and one at each of the main span piers only. The pier that was struck by the barges was an unprotected approach span pier.

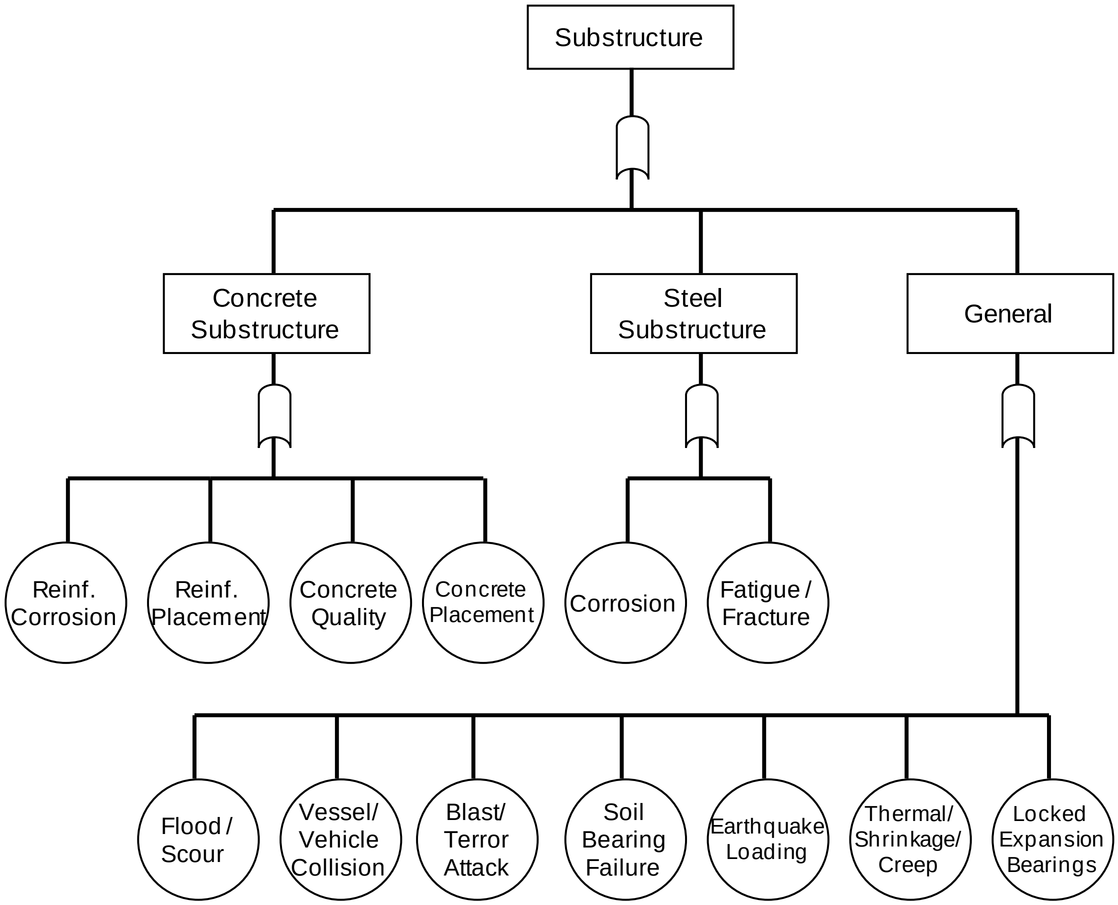


Figure 7: Substructure Portion of Typical Girder Fault Tree

More sophisticated analyses may be warranted for complex and/or significant structures that could be subject to collision loads. The bridge designer and/or owner must also consider the use of protective devices. Fender type systems consisting of rubber, steel, or concrete, or dolphin type protection systems can reduce collision force effects in the pier by absorbing the impact energy. Protective islands can be effective in vessel collision protection. Crash walls can be designed to resist vehicle and train loads for overpass structures. Furthermore, a framed structure such as a concrete box girder bridge with an integral pier cap is more likely to distribute a collision load throughout the structure than a girder-slab structure.

Complex Bridges – Lessons Learned

For complex bridges, such as trusses, arches, suspension, and cable stayed, fault trees are not developed, as many of the potential failure mechanisms shown in the steel and precast girder fault trees can also apply to complex bridges. A “lessons learned” approach is employed for complex bridges within the *Framework*. Some of the lessons learned from complex bridge failures are provided herein.

Quebec Bridge Collapse

The Quebec Bridge collapsed on August 29, 1907 during construction, killing 75 workers. The Quebec Bridge was a three-span cantilever truss, with an 1800 ft center span. (Pearson and Delatte 2006) provide a detailed account of the Quebec Bridge failure, including events that led up to the failure, highlights of the commission's report, causes of the failure, and ethical aspects.

As a result of the Quebec Bridge collapse, research regarding column buckling was initiated. Among other findings, the collapse demonstrated the importance of communication during erection. If problems are noticed in the field by workers, supervisors, or inspectors, the problems need to be investigated immediately by the engineers. A successful bridge project, from design to final construction, requires the entire team to be working together and communicating effectively.

Tacoma Narrows Bridge Collapse

The collapse of the Tacoma Narrows Suspension Bridge occurred on November 7, 1940, over the Puget Sound Washington State (Scott 2001, Lwin 2011). The bridge opened on July 1, 1940, had a total length of 5,000 ft, and a center span length of 2,800 ft. The Tacoma Narrows Bridge was the first suspension bridge to use steel plate girders to support the roadway while previous suspension bridges typically used steel trusses to support the roadway. The plate girders used in the bridge were 8 ft deep. The dead load and stiffness of the bridge were much less than other suspension bridges built previously.

The collapse of the Tacoma Narrows Bridge initiated the consideration of aerodynamics in long-span bridge design. Wind not only causes static loads on a bridge, but results in a special dynamic behavior as well. The collapse shows bridge designers the importance of stiffness, rigidity, torsional resistance, and dampening in suspension bridges as they relate to wind. Addressing these issues can be accomplished through wind tunnel testing, and computer modeling that integrates the wind tunnel test data.

Closing Remarks

The *Framework* serves as a general checklist of issues that should be given attention by a bridge designer during the design process in order to minimize potential failures during the service life and/or construction of the specific bridge being designed. Fault-trees allow the designer to graphically see various failure combinations and failure paths. The *Framework* can help a bridge designer and/or owner to determine whether additional analyses investigating potential failures are warranted.

The *Framework* provides an introduction to the concept of incorporating fault-tree analysis and lessons learned into everyday bridge design. General fault-trees describe the potential contributory factors that designers can use to address potential sources of failure during the design process. Illustrative examples of fault-tree analysis have been provided for several types of bridges, including superstructures and substructures. The illustrative examples provide the tools for identifying potential failure modes, and give suggestions for giving due considerations in the design to prevent such potential failures and to improve the resilience of the design.

The *Framework* is intended to be informative and educational to bridge owners, bridge designers, inspectors, fabricators, contractors and maintenance personnel, as well as students and instructors of bridge engineering. A copy of the *Framework* may be downloaded from http://www.fhwa.dot.gov/bridge/pubs/hif11016/hif11016.pdf.

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