Case Study

Fault-Tree Model for Risk Assessment of Bridge Failure: Case Study for Segmental Box Girder Bridges

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Abstract: Over the past few decades, the design capacity and service condition of many bridges, which are vital components of the surface transportation infrastructure reliability and functionality, have been challenged by rapid traffic growth and scarce maintenance funds. Numerous incidents of bridge collapse call for an urgent need to develop a systematic method of assessing the failure risks and identifying the initiating events that can lead to a bridge collapse. This paper presents a process of bridge failure risk analysis through fault-tree modeling for a common type of bridge known as segmental concrete box girder bridge. The process was applied to a segmental box girder bridge in South Carolina and was found to effectively identify causal factors of bridge failure and estimate overall failure risk. However, to comprehensively assess the probability of bridge failure, fault-tree analysis can best be used in combination with current risk assessment methods, such as visual inspections and structural health monitoring sensors. **DOI: 10.1061/(ASCE)IS.1943-555X.0000129.**

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Introduction

Bridges are vital components of the U.S. surface transportation system and support the growth of this nation's economy. Because of the increased freight transportation over the past few decades, the current demands imposed on many of the bridges in terms of the load magnitude and frequency are much higher than they were initially designed to support. As a result, more than 1,400 bridges in the United States have collapsed since 1970 (Sharma and Mohan 2011), which demonstrates a critical need to develop a systematic method of assessing the failure probability and identifying the initiating events that can lead to a bridge collapse. A proactive infrastructure management system is needed to develop a sustainable national transportation network. It is important to focus on facilitating a bridge failure risk assessment method that can be implemented efficiently and effectively by infrastructure managers.

A fault tree is a risk assessment tool that depicts a failure event by combining different causal factors. It can be used both qualitatively and quantitatively to assess bridge failure. To the authors' knowledge, previous studies that have assessed bridge failures using fault trees were for forensic analysis or analysis of individual subcomponents, such as beams, decks, and piers (Johnson 1999; LeBeau and Wadia-Fascetti 2007). The study presented in this paper uses fault-tree analysis (FTA) as a risk prediction tool for the whole bridge over its lifetime. Identification of causal factors will allow countermeasures that will most effectively minimize the overall risk of bridge failure to be determined. The occurrence probabilities of casual factors and the whole bridge system could be used to optimize inspection programs by focusing inspections on factors more probable to cause failure and only performing inspection when the overall bridge condition is approaching an unsafe level. The focus of this paper is to present a process to analyze the risk, identify the causal factors, and estimate the time-to-failure of a bridge through FTA. A case study has been developed for segmental concrete box girder bridges by using a bridge in Charleston, South Carolina.

Background

Fault-Tree Analysis

Fault-tree analysis can be used to perform two types of analyses—qualitative and quantitative. Qualitative analysis produces a graphical Boolean depiction of the factors (events) leading to bridge failure (top event). Each event is connected to an upper-level event by an OR, AND, EXCLUSIVE OR, INHIBIT, and PRIORITY AND gates. The events that make up the fault tree are classified as intermediate, basic, undeveloped, conditional, or house events. In this paper the OR and AND gates and intermediate, basic, and undeveloped events are used (Fig. 1). Cut sets are used to describe unique combinations of events that cause the top event to occur. Minimal cut sets are those combinations that have the shortest path to the top event. Quantitative analysis is performed by determining the occurrence probabilities of all basic, undeveloped, conditional,

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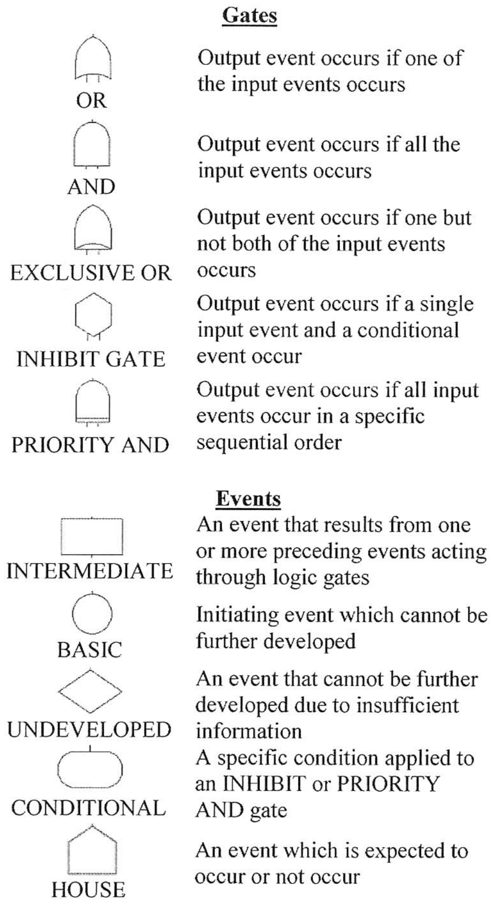

Fig. 1. Fault-tree gates and events

and house events and by using Boolean algebra and probabilistic mathematics to solve for the occurrence probability of the top event and cut sets. The occurrence probability of cut sets provides insight into which minimal cut set is most likely to occur.

Advantages of FTA over Current Bridge Assessment Methods

Current bridge risk analysis methods and tools can be characterized into three categories: field inspections, computer simulations, and real-time monitoring by using on-site sensors. The purpose of the visual field inspections is to look for signs and symptoms of deterioration that could lead to failure. Real-time monitoring sensors, such as structural health monitoring (SHM) sensors, look for symptoms by using sensors on the bridge that can be connected to a computer network. Computerized models and simulations predict failure on the basis of historical data and trends. Two examples of computerized simulation models that have been developed are Pontis (Futkowski and Arenella 1998; Cambridge Systematics, Inc. 2004) and artificial neural network (ANN) (Huang 2010). In addition to historical data and trends, computerized knowledge-based systems compile and input expert opinions and results from other methods (e.g., field inspections). *BRIDGIT* is a two-component computerized knowledge-based system (de Brito et al. 1997). Although these risk analysis methods have advantages, they still have several limitations that have not been addressed. The use of FTA could resolve most of these issues. Some of the limitations and solutions FTA provides are the following:

- The computerized mechanistic-based simulations and knowledge-based systems require a significant amount of technical data. In FTA, if the exact information is not known, an educated guess or probable range can be input for the probability of basic events.
- Structural health monitoring, computerized mechanistic-based simulation, and sometimes visual inspection do not identify the chain of events that lead to bridge failure. The FTA model is developed using the chain of events; therefore, the events leading to failure can be identified through analysis.
- Many of the visual inspections, computerized simulations, and computerized knowledge-based systems discussed only assess the condition of individual bridge components instead of assessing the components both individually and in relation to each other. Fault-tree analysis can be used to assess the condition of individual components and the cause-and-effect relationships between the different levels of events.
- Except for some computerized simulations, all the methods mentioned are not known to use or produce a visual model of the bridge system. Fault-tree analysis produces a fault-tree model, which visually shows the individual bridge components with the chain of events leading to their failure and ultimately of the bridge, and the relationships between the various causal events and bridge components.

In addition to these resolutions, FTA has the benefit of being quick and easy to use. Although FTA is shown to have many advantages, it also has some limitations. The first disadvantage noticed when using FTA is the significant amount of background knowledge required on the bridge before the fault-tree can be constructed. Another shortcoming of FTA is the difficulty in finding probabilities for each event during quantitative analysis caused by the lack of research material or large amounts of data that must be analyzed. Visual inspections can provide a lot of the data needed for FTA; therefore, FTA is best used in combination with visual inspections.

Risk Assessment Process and Methodology

The first step in risk assessment is to research and identify plausible causes of bridge failure for the bridge type of interest, which helps to develop the qualitative structure of the fault tree. Once the qualitative part of the fault tree is developed, minimal cut sets can be identified and probabilities can be assigned to basic events. Identification of the minimal cut sets with the highest probability of failure allow for prioritization of countermeasures.

Fault-Tree Development

Before the fault tree can be qualitatively developed, a general knowledge of the bridge and its structural components is necessary. In addition, a list of plausible failures and their causes must be compiled. Expert opinion, failure case studies, and inspection reports are some sources of this information.

Once the different failure components and causes have been identified, the fault tree can be developed. The fault tree starts with the top event, bridge failure, and is broken down into primary bridge components that can lead to bridge failure if the component fails. Each component is then broken down into events that can directly lead to the component failure. The appropriate gate is chosen to link each primary component event to their causal events. The cause-and-effect process continues until none of the events can be broken down further. The bottom events are then defined as basic, undeveloped, or house.

The fault tree does not have to contain all events that could possibly occur but only those that could occur within reason. If an event has not previously shown to be a problem with similar bridges, then the event may be excluded. A common rule is to use the minimum number of events necessary. Another common

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practice is to avoid using the same event more than once because the event is counted in the analysis as many times as it occurs, which results in biased quantitative results. To avoid duplication of an event, such as a collision, which can affect multiple bridge components, the component affected should be specified.

Minimal Cut Sets

Minimal cut sets are the shortest combination of events leading to the top event. These combinations are found by using Boolean algebra. In this study, minimal cut sets were calculated by using *FaultTree+* software (Isograph 2008). A variety of fault-tree softwares are available for constructing fault trees and computing their cut sets.

Occurrence Probabilities

The sources that can be used to develop probabilities for fault-tree events are public databases, experimental data, model analysis, expert opinion, and published research findings. Most often, probabilities found in these sources are not directly applicable to the basic event; therefore, statistical and probabilistic analyses must be used to estimate the occurrence probabilities of the basic events. The procedure used to determine the occurrence probabilities on the basis of published findings is discussed in the following example.

Consider an example in which scour and inadequate foundation create a minimal cut set with a high probability of occurrence. For this example, the probability of inadequate foundation depth caused by scour was calculated by using data from three studies (Sharma and Mohan 2011; Harik et al. 1990; Wardhana and Hadipriono 2003) on bridge failures in the United States. Table 1 shows the average number of bridges and number of failures caused by scour for each surveyed period. The average number of bridges in a given period was calculated by using data from the studies and the National Bridge Inventory (NBI) database [Federal Highway Administration (FHWA) 2011]. All the data collected and computed were used to develop the annual probability of bridge failure caused by scour.

The annual probability of failure caused by scour of all the bridges in the United States was estimated by using the following:

$$P_{f,N} = 1 - (1 - P_{f,A})^N \tag{1}$$

where $P_{f,N}$ = probability of failure for a given period range; $P_{f,A}$ = annual probability of failure; and N = period in years. Eq. (1) assumes that the annual scour failure probabilities from year to year are independent and uncorrelated. This assumption is not entirely true because the scour failure probability will vary over time as deterioration occurs or maintenance is performed. For simplicity, it is assumed that major maintenance is not performed over the considered period. Thus, the annual failure probability can be modeled as an identical and independently distributed variable. Solving for $P_{f,A}$, the equation becomes

$$P_{f,A} = 1 - (1 - P_{f,N})^{1/N} \tag{2}$$

The annual probability of bridge failure caused by scour calculated for each study is shown in Table 1. The average annual probability calculated can then be input into the fault tree.

Countermeasures

To prioritize implementation of countermeasures, the minimal cut sets must be identified. Once the minimal cut sets are identified, historical data on bridge failures can be used to develop probabilities for the occurrence of the cut sets. Countermeasures that are expected to have the largest impact on the health of the bridge should be implemented. In some cases, one countermeasure may be applied to a bridge to reduce the occurrence of multiple causal factors. Possible countermeasures for existing bridges include maintenance, retrofits, and intelligent sensors. For future bridge projects, countermeasures can also include changes in bridge design and construction methods. The application of these countermeasures reduces the risk of bridge failure.

Application of FTA to Segmental Concrete Box Girder Bridge–Case Study

The fault-tree-based bridge risk analysis process was applied to a segmental concrete box girder bridge in South Carolina to assess the efficacy of the FTA process in analyzing causal factors and assessing overall failure risk. The James B. Edwards Bridge of Charleston, South Carolina, constructed in 1989 consists of two posttensioned side-by-side concrete segmental box girders. The bridge services a section of I-526, which crosses over Wando River (salt water) and two two-lane roads (one at each end of the bridge). Because the bridge crosses the Wando River closer inland, there is minimal commercial-vessel traffic beneath the bridge. The two-lane underpasses are also lightly traveled. There have not been reports of any collisions to the piers. The problems that have been identified through inspections by the SCDOT are (1) improper grouting of ducts, (2) leaky joints, (3) debris in the box void, (4) clogged drain holes (3/4-in. diameter), and (5) cracks in the piers.

Fault-Tree Development

Obtaining knowledge about the structure and service history of bridges similar to the case study bridge is important for the development of the fault tree. Segmental box girder bridges consist of multiple segments aligned longitudinally across the bridge span. The segmental box girders are connected through shear keys, longitudinal posttensioning tendons, and epoxy-filled joints. Segmental box girders can also be individually posttensioned transversely. The sealing of the keyways and joints with grout or epoxy helps the segments to resist against vertical shear forces.

Table 1. Number of Bridge Failures Caused by Scour

Period	Period range (years)	Average number of bridges[a]	Number of failures	$P_{f,N}$	$P_{f,A}$
1951–1988[b]	37	587,717	6	1.02×10^{-5}	2.80×10^{-8}
1989–2000[c]	11	592,966	78	1.32×10^{-4}	1.20×10^{-5}
1800–2009[d]	209	600,119	209	3.33×10^{-4}	1.59×10^{-6}
				Average	4.61×10^{-6}

[a]See FHWA (2011).
[b]See Sharma and Mohan (2011).
[c]See Wardhana and Hadipriono (2003).
[d]See Harik et al. (1990).

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Together, the shear keys and posttensioning tendons enable service loads to be distributed among the segments. To protect the shear keys and joints, current practice is to apply a waterproof barrier on top of the girder system before placement of a wearing surface (asphalt or concrete topping); however, some bridges have been constructed without a waterproof barrier.

Concrete box girder bridges have a noticeably high number of collapses and closures. According to Sharma and Mohan (2011), as of 2009, 21 concrete box girder bridges have failed since the first was constructed in 1950. The failure cases were located in Colorado, Florida, Illinois, Indiana, New York, Ohio, Pennsylvania, and Virginia (Naito et al. 2010; Russell 2009). The leading causes of failure for all bridge types are hydraulic events (54%), collisions (14%), overloading (12%), and deterioration (5%) (Sharma and Mohan 2011). For prestressed concrete box girder bridges, deterioration seems to have a higher impact on failure, especially in the Northeast. (Naito et al. 2011). A survey by Russell (2009) showed that the skew of the bridge, presence of concrete or asphalt topping, performance of the waterproof membrane, and bridge maintenance are the four key factors thought to have the most influence on long-term bridge performance. The survey results also found longitudinal cracking along the grouting of adjacent beams and leakage of water and chlorides through joints to be the two most common problems observed (Russell 2009). Although engineers have learned from the concrete box girder bridge incidents and made changes to the design and construction procedures, failure concerns still exist.

Some of the failure modes that are known for posttensioned concrete box girders are waterproofing membrane, concrete, shear key, and prestressed/posttensioned tendon failures. The main cause of waterproofing membrane failure is large beam displacements caused by overstressed/overloaded beams [Michigan Department of Transportation (MDOT) 2005]. Overstressing of beams can also cause cracking of the concrete. Other causal factors are temperature variants, insufficient reinforcement, premature releasing of prestressing strands during curing, loss of prestress, concrete shrinkage during curing, and concrete deterioration (MDOT 2005). The cracks expose the interior concrete and grout to water, chlorides (deicing salts), and acidic gases (CO_2), which cause deterioration. At this stage, shear key failure can occur because of deterioration of the shear key grout, which eventually leads to corrosion of tendons. Once the water and chlorides get through the shear key, they can enter through splits in the duct sleeves, unsealed duct joints, and unsealed grout inlets/outlets used for placing grout inside the ducts (Corven and Moreton 2004). Once the water and chlorides get into the duct, they begin to degrade the grout and corrode the tendons. The discussed chain of events leading to tendon corrosion started external to the duct; however, the corrosion process can also begin within the duct. If the grouting of the duct is not properly executed, voids can be created in the grout because of excess water and bleeding (Corven and Moreton 2004). These failure modes are just a few of the ways failure can occur.

Fault-Tree Qualitative Analysis

Failure of a bridge (system failure) is usually initiated by failure of key superstructure or substructure components, such as the beams, abutments, piers, bearing pads, and foundation. Beam collapse is caused by overloading by high traffic loads and reduced strength from extreme heat, collisions, and corrosion of posttensioning tendons and reinforcement. Foundation failure is the result of scour, which is caused by water flow eroding the foundations. When the foundation depth is shallow enough that the abutment or pier can move vertically, failure can occur (LeBeau and Wadia-Fascetti 2007). The major cause of bearing failure is extreme lateral forces that knock the superstructure off the bearings (LeBeau and Wadia-Fascetti 2007). The extreme lateral forces can come from environmental or collision events. The collision events can also cause local damage to abutments or piers, which can result in failure. Another source of abutment and pier failure is corrosion.

Superstructure Failures

As mentioned, overloading and reduced beam strength caused by fatigue or repetitive loading may lead to beam failure. The high traffic loads that result in overloading refer to traffic loads exceeding the design load. Over time, the amount of traffic that bridges must handle can increase beyond the design capacity. The strength of the beam can be reduced by temperatures greater than the maximum design temperature of 120°F, which has been defined as extreme heat in the fault tree (LeBeau and Wadia-Fascetti 2007). Collisions and corrosion also have an effect on beam strength. Collisions, for this case study, refer to marine vessels or trucks producing large-impact forces on the girders, which are a result of height-limit violations, accidents, or intentional attacks. Corrosion occurs when water with high chloride concentrations have access to reinforcement and interact with the iron in the strands (Sianipar and Adams 1997). The source of water is usually wet weather conditions (e.g., rain, snow, ice) or bodies of water. Inflated chloride levels are a result of roadway salts applied during icy weather conditions. As ice on the roadway melts, the salts are washed away with water. These causes of failure were used to develop the fault tree shown in Figs. 2 and 3.

The main entry point for chloride water is through cracks in the concrete, waterproof barrier, and joint/keyway sealant, which are initiated by overstressed beams undergoing large displacements (MDOT 2005). Another key entry point is through insufficient concrete cover, which is a result of faulty construction. When chloride water passes through the waterproof barrier (if present) and joints/keyways, it enters the box girder void. A waterproof membrane that is defective or nonexistent allows chloride water to reach the underlying concrete and joints. The case study bridge has wet joints, which are joints "sealed" with a material such as grout or epoxy. When the grout/epoxy has cracks, chloride water flows through the cracks and further deteriorates the fill material, allowing water to flow completely through the joint and enter the girder void. There are two concerns with the chloride water entering the void: (1) internal reinforcement corrosion and (2) posttension tendon corrosion.

Internal reinforcement corrosion is the result of insufficient drain sizes, which can lead to debris and other material clogging the drain and allowing chloride water to sit and penetrate the concrete. When this occurs, not only is the loading imposed on the superstructure increased from the captured water, the corrosion process is expedited (Sianipar and Adams 1997).

Tendon corrosion starts when the water in the void comes in contact with interior ducts. Water can enter the ducts through splits, unsealed joints, or unsealed grout inlets/outlets (Corven and Moreton 2004). Once the water enters the duct, it degrades the surrounding grout, allowing direct access to the posttensioning tendons. Often, the ducts are not properly grouted during construction, which allows water from grout bleeding or external sources to have more direct access to the tendons.

Substructure Failures

As previously stated, foundation failure is caused by scour, which can be characterized as one of the following: (1) contraction scour, (2) local scour, (3) degradation, (4) channel widening, and (5) lateral migration (Johnson 1999). The causes of contraction and local scour, respectively, are flow constrictions and obstruction in the

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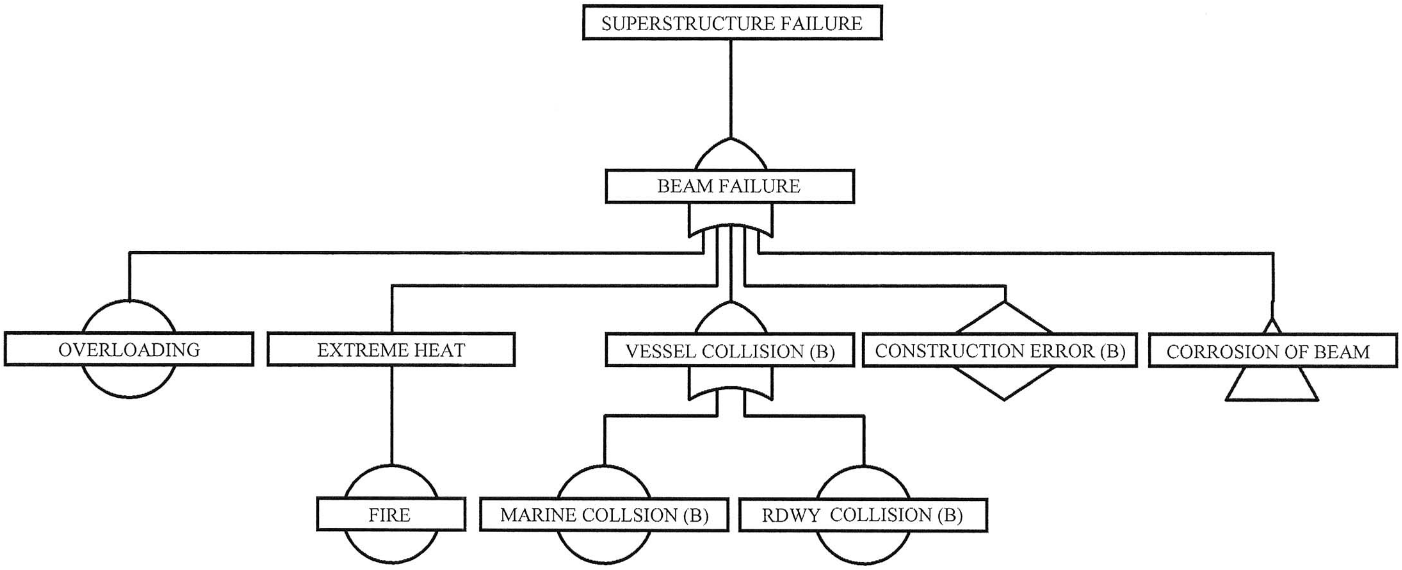

Fig. 2. Fault-tree model for James B. Edwards Bridge superstructure

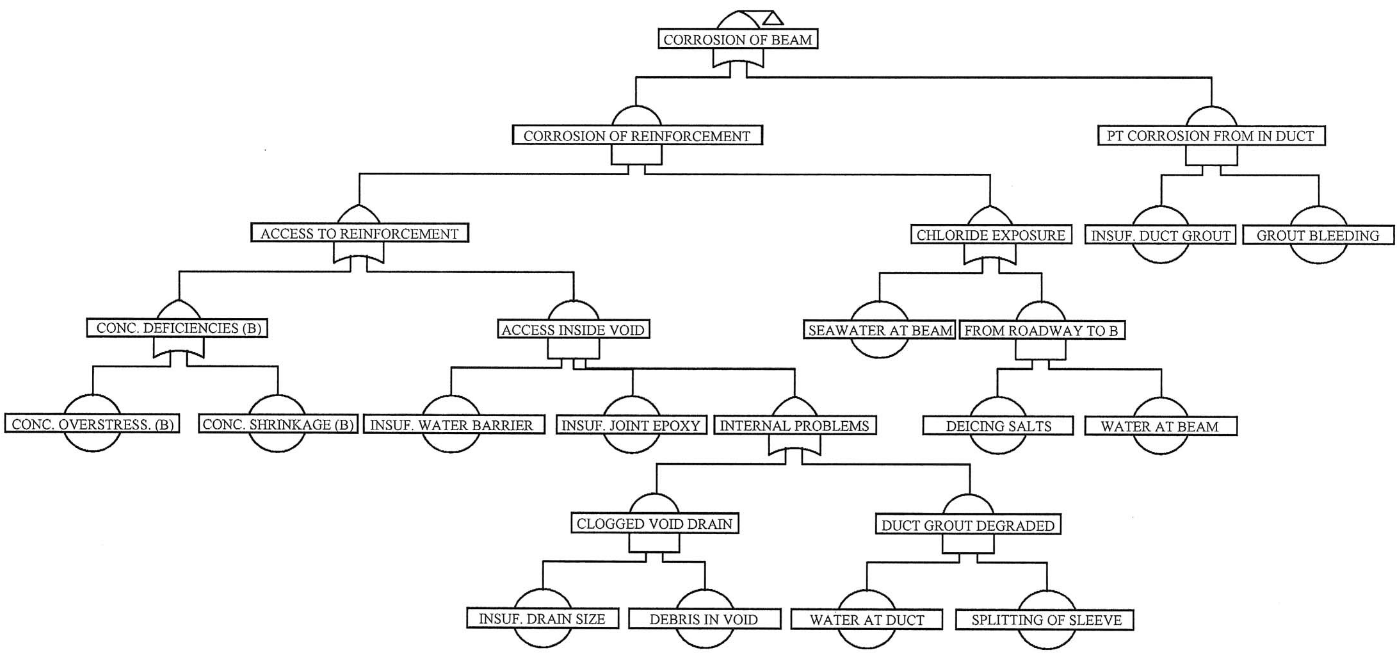

Fig. 3. Fault-tree model for corrosion of James B. Edwards Bridge superstructure

flow caused by bridge substructure. Degradation, channel widening, and lateral migration are natural-occurring events. Degradation affects the foundations by lowering the entire channel bed. Channel widening and lateral migration have greater effects on the abutments and piers that were not designed to be exposed to the channel flow. The amount of scour present depends on several factors, such as the flow characteristics, channel dimensions, and channel bed soil properties.

Environmental events with large lateral forces, such as storm surges, floods, and earthquakes, have been stated to cause bearing failure (LeBeau and Wadia-Fascetti 2007). The extreme lateral forces seen by collisions can cause bearing, abutment, and pier failures, in which bearing failure is caused by misalignment of the bearing pads and abutment and pier failures are caused by severe local damage of the components. In addition to collisions, corrosion can also cause abutment and pier failures. Corrosion occurs when chloride water enters cracks in the abutments or piers. Insufficient concrete cover from construction errors can also allow penetration of the chloride water. These events were used to develop the fault-tree model shown in Figs. 4 and 5.

Finalized Fault Tree for Quantitative Analysis

Adjustments were made to the qualitative fault tree for the quantitative analysis because of the lack of probabilistic data for some of the basic events. The events with insufficient probabilistic data were primarily related to corrosion. The majority of corrosion research looks at understanding corrosion development mechanisms, such as impacts of different composition of metals (Sagüés et al. 2009; Hansson et al. 2006), use of admixtures, type of concrete cover (Jaffer and Hansson 2009), and environmental factors. Moreover, site/location-specific studies on the probability of most corrosion causal factors are not available in literature. Because the main focus of this case study is to evaluate the use of FTA to predict the failure probability of a bridge, in depth focus was not given to the complex corrosion events for quantitative analysis. The finalized fault tree for quantitative analysis, shown in Figs. 6 and 7, used undeveloped events to model corrosion events. The expanded fault tree could be pursued with future research on probabilities for in-depth corrosion factors.

Minimal Cut Sets

For the complete qualitative fault tree, the most influential cut sets consisted of 11 single-event cut sets: construction error for abutment/piers and beams, earthquake, fire, marine collision for abutment/piers and beams, overload, roadway collision for abutment/piers and beams, scour, and storm surge. The complete list of minimal cut sets for the qualitative fault-tree is shown in Table 2. Minimal cut sets with the same number of events are considered to be equally influential to the top event in qualitative analysis. During quantitative analysis, the ranking of events can change depending on their probability of occurrence. The finalized fault tree, which will be used for quantitative analysis of this case study, consists of only single-event cut sets; therefore, each basic event is considered a probable component failure that may cause the top event, that is, bridge failure.

Occurrence Probabilities

Occurrence Probabilities of Basic Events

Quantitative analysis was used to rank the minimal cut sets according to their probability of occurrence. The sources used to develop probabilities for fault-tree events were (1) studies on bridge failures, (2) bridge inspection reports, and (3) expert opinion. The works of Harik et al. (1990), Wardhana and Hadipriono (2003),

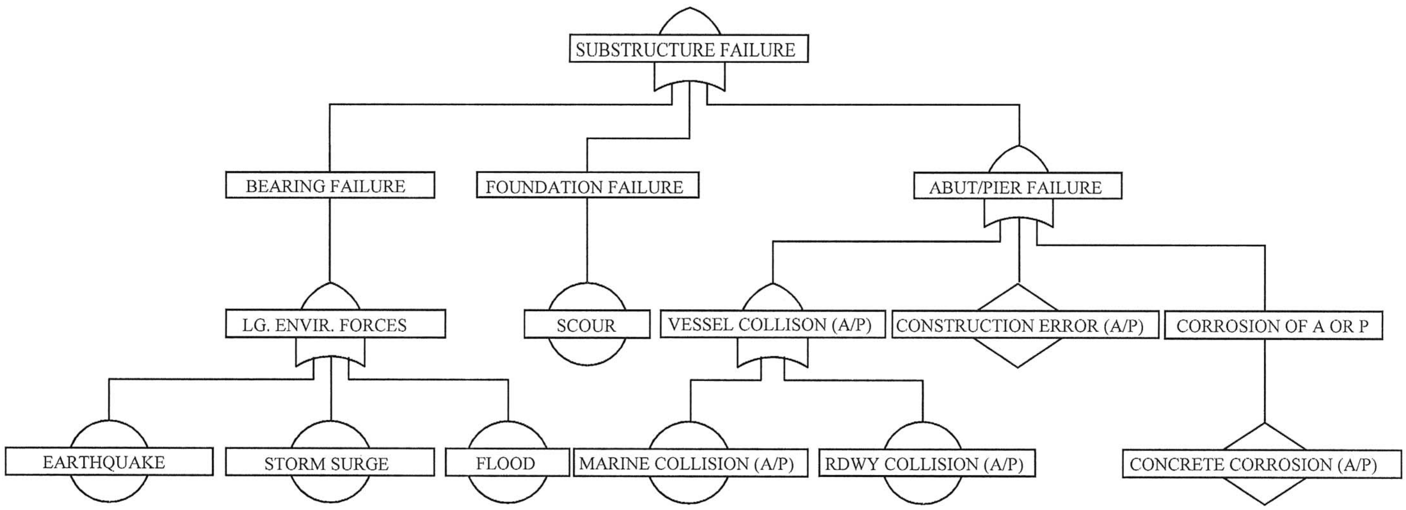

Fig. 4. Fault-tree model for James B. Edwards Bridge substructure

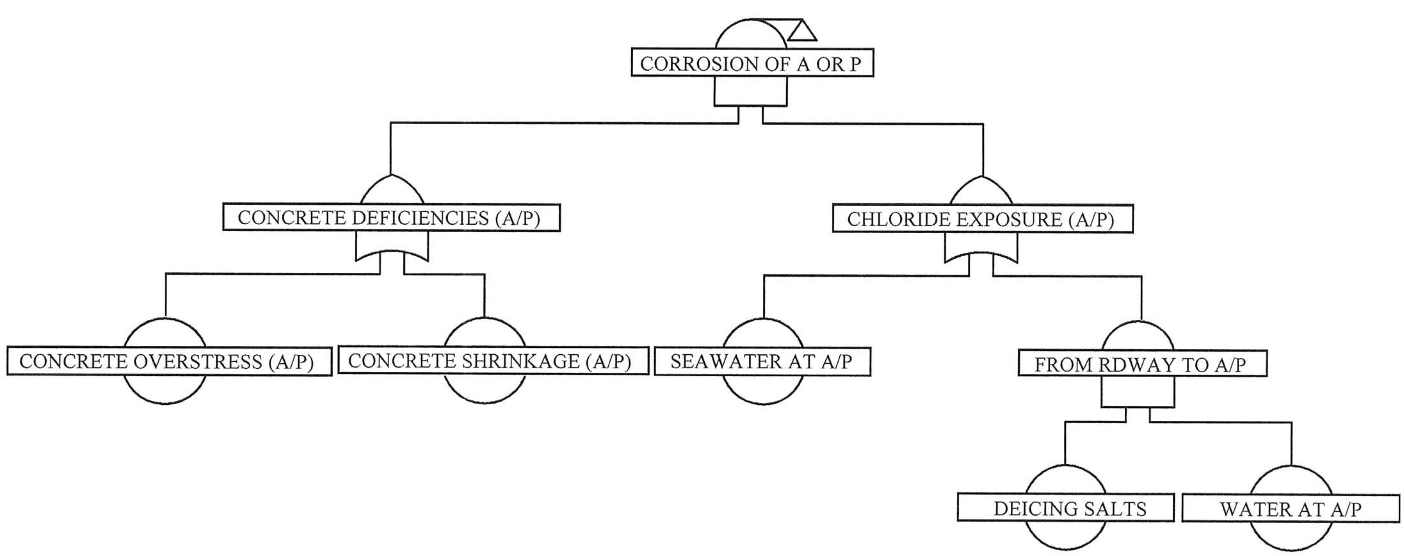

Fig. 5. Fault-tree model for corrosion of James B. Edwards Bridge substructure

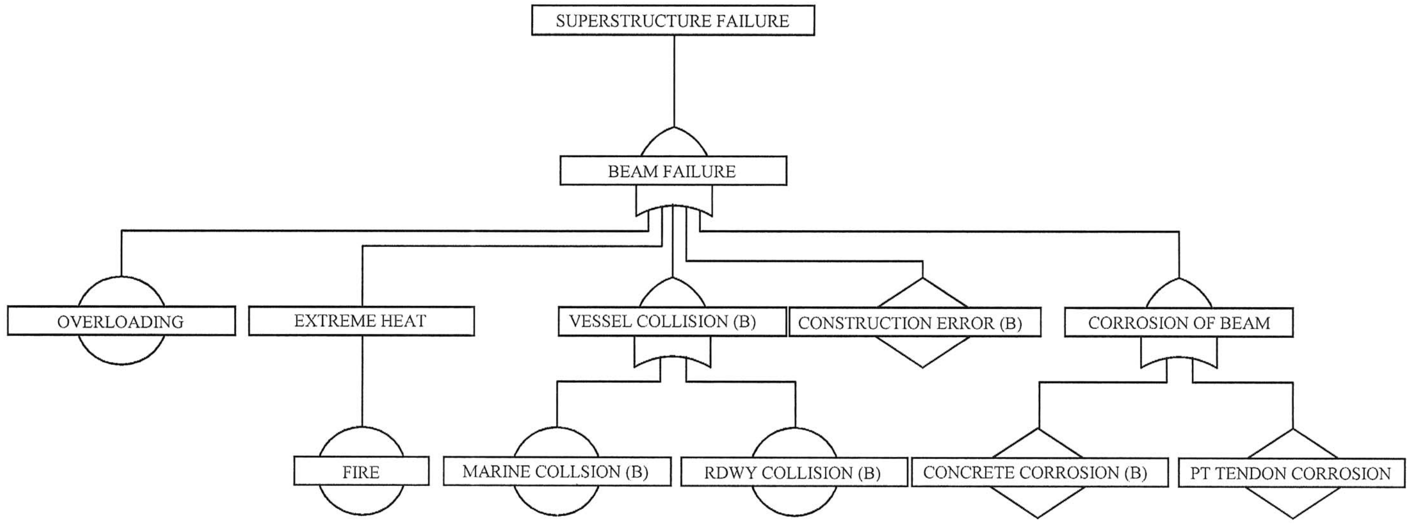

Fig. 6. Finalized fault-tree model for James B. Edwards Bridge superstructure

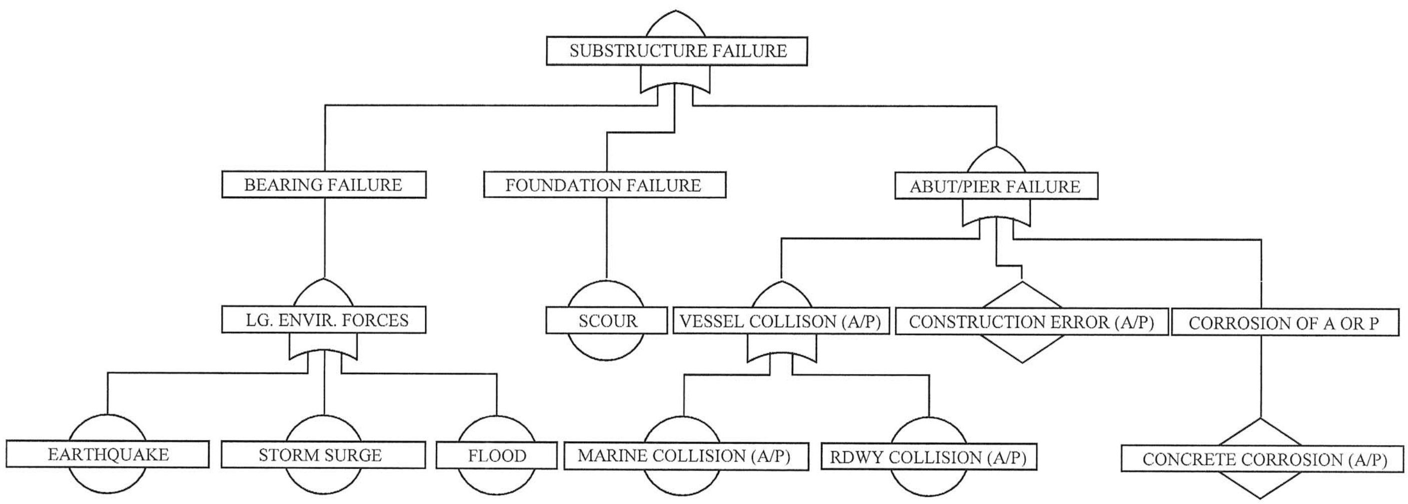

Fig. 7. Finalized fault-tree model for James B. Edwards Bridge substructure

and Sharma and Mohan (2011) were consulted for analysis of bridge failures in the United States. Information on posttensioned tendon failure was gathered from Woodward (2001). Before calculating the annual probabilities, each event was assumed to follow a certain trend. For this fault tree, the occurrence probability of each event was assumed either to be constant, for a time-invariant event (e.g., construction error), or to follow Eq. (1). The annual failure probabilities, $P_{f,A}$, were estimated by using the procedure for published failure statistics discussed in the "Occurrence Probabilities" section. Constant trends were calculated by taking the average of the $P_{f,N}$ values. Because some of the data, such as roadway collision, were not broken down into the components (i.e., beam or pier) they affect, the resulting probabilities were divided among the components according to field observations of the James B. Edwards Bridge. The trend, ratio, and annual probability for each basic event are listed in Table 3.

Occurrence Probabilities of Bridge System Failure

Infrastructure safety is often measured in terms of a structural reliability index, β, which is defined by

$$\beta = \Phi^{-1}(1 - P_f) \tag{3}$$

where $\Phi^{-1}(\cdot)$ = inverse function of the standard normal cumulative density function (CDF); and P_f is the probability of failure. A beta value of 3.1 has been accepted by the International Organization for Standardization (ISO) as the target reliability index under ISO 2394 (ISO 1998); therefore, a bridge with a beta value of less than 3.1 is considered structurally unsafe. The equivalent probability of failure is 1.00×10^{-3}, in which a probability of failure of greater than 1.00×10^{-3} is considered unsafe.

Because the bridge is currently in service and considered safe by the South Carolina DOT, the fault-tree result for bridge failure at 22 years of age was expected to be less than 1.00×10^{-3}. The AASHTO LRFD Code (AASHTO 2010) states that a bridge should be designed for a life of 75 years. Previous studies (Wardhana and Hadipriono 2003; Sharma and Mohan 2011) show that many bridges begin to fall below the accepted safety factor of 1.00×10^{-3} at approximately 50 years. The fault-tree results were as expected at the age of 22 years, with a failure risk of 5.85×10^{-4}. The analysis at 50 years of age showed that the bridge was approaching an unsafe structural state, with a failure risk of 1.21×10^{-3}, which is was accepted on the basis of previous studies.

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Table 2. Minimal Cut Sets for Qualitative Fault Tree

Number of events	Cut sets descriptions
1	Construction error (A/P)
	Construction error (B)
	Earthquake
	Fire
	Marine collision (A/P)
	Marine collision (B)
	Overload
	Roadway collision (A/P)
	Roadway collision (B)
	Scour
	Storm surge
2	Grout bleeding ∩ insufficient duct grout
	Seawater at A/P ∩ concrete overstressing (A/P)
	Seawater at A/P ∩ concrete shrinkage (A/P)
	Seawater at beam ∩ concrete overstressing (B)
	Seawater at beam ∩ concrete shrinkage (B)
3	Deicing salts ∩ water at A/P ∩ concrete overstressing (A/P)
	Deicing salts ∩ water at A/P ∩ concrete shrinkage (A/P)
	Deicing salts ∩ water at beam ∩ concrete overstressing (B)
	Deicing salts ∩ water at beam ∩ concrete shrinkage (B)
5	Seawater at beam ∩ insufficient joint epoxy ∩ insufficient water barrier ∩ debris in void ∩ insufficient drain size
	Seawater at beam ∩ insufficient joint epoxy ∩ insufficient water barrier ∩ splitting of sleeve ∩ water at duct
7	Deicing salts ∩ water at beam ∩ insufficient joint epoxy ∩ insufficient water barrier ∩ debris in void ∩ insufficient drain size
	Deicing salts ∩ water at beam ∩ insufficient joint epoxy ∩ insufficient water barrier ∩ splitting of sleeve ∩ water at duct

Note: A/P = abutment/pier; B = beam.

Countermeasures

Minimal cut sets with the highest probability of failure were identified for prioritization of countermeasures. The top ten cut sets based on their probabilities for the case study bridge are shown in Table 4. The prioritized list of cut sets along with benefit-cost analysis should be used to help identify the most efficient and cost-effective countermeasures whether it be implementation of special inspections, maintenance activities, retrofits, or structural health monitoring sensors. The countermeasures can be applied to the fault tree to calculate how much the probability of bridge failure is reduced when they are applied to the bridge.

Table 3. Annual Failure Probabilities Used for FTA

Failure mode	$P_{f,A}$	Trend notes
Construction error (A/P)	2.60×10^{-5}	Time invariant
Construction error (B)	2.60×10^{-5}	Time invariant
Earthquake	1.38×10^{-6}	Time dependent[a]
Fire	3.90×10^{-5}	Time dependent[a]
Flood	1.04×10^{-5}	Time dependent[a]
Marine collision	4.36×10^{-5}	Time invariant
Marine collision (A/P)	1.63×10^{-7}	0.75 of marine collision
Marine collision (B)	5.43×10^{-8}	0.25 of marine collision
Overload	3.18×10^{-6}	Time dependent[a]
PT tendon corrosion	2.40×10^{-6}	Time dependent[a]
Reinforcement corrosion	1.09×10^{-7}	Time dependent[a]
Roadway collision	6.64×10^{-5}	Time invariant
Roadway collision (A/P)	1.73×10^{-7}	0.40 of roadway collision
Roadway collision (B)	2.61×10^{-7}	0.60 of roadway collision
Scour	4.61×10^{-6}	Time dependent[a]
Storm surge	2.17×10^{-7}	Time dependent[a]

[a]Eq. (1) is used to calculated the failure probability at time N by using the annual failure probability.

Table 4. Top 10 Cut Sets Based on Risk

Rank	Minimal cut set	Probability of occurrence at age 50 years
1	Flood	5.20×10^{-4}
2	Scour	2.30×10^{-4}
3	Overload	1.59×10^{-4}
4	PT tendon corrosion	1.20×10^{-4}
5	Earthquake	6.91×10^{-5}
6	Fire	3.90×10^{-5}
7	Construction error (A/P)	2.56×10^{-5}
8	Construction error (B)	2.56×10^{-5}
9	Storm surge	1.09×10^{-5}
10	Concrete corrosion (A/P)	5.43×10^{-6}

Inspections can be focused on the factors that are more probable to lead to structural failures. Concentrating on these factors allows for elimination of unnecessary inspection procedures and creates more-targeted, beneficial, and cost-effective inspections. The quantitative results for the whole bridge system can be used to estimate the remaining life of the bridge, which can be used to optimize the inspection schedule by only inspecting bridges when their reliability index or failure risk is approaching an unsafe level.

Segmental concrete box girder bridges are common in many parts of the United States. The causal factors identified and prioritized through the segmental concrete box girder bridge in the case study can contribute to future research, design, maintenance, and inspection of similar bridges to improve their safety.

Conclusions

Bridges are one of the most critical components in the transportation infrastructure for safety, security, and mobility. Different issues, such as increased truck loadings and reduced maintenance funds, have contributed to increased risks of bridge failure, compromising the safety of travelers and the growth of the economy. This paper presents a case study for a fault-tree-based predictive risk assessment approach and a case study of causal factor analysis for a posttensioned segmental concrete box girder bridge that uses the approach. The case study suggested that the top five critical factors leading to segmental concrete box girder bridge failure, from most to least critical, are as follows: flood, scour, overloading, corrosion of post-tensioning tendons, and earthquake. The overall failure risk identified through FTA was consistent with past bridge failure trends. The analysis showed the bridge approaching an unsafe structural state at 50 years, with a 1.21×10^{-3} probability of failure.

Although the causal analysis of failure through fault tree can help identify countermeasures to minimize failure risks, it is best used in combination with current methodologies, such as visual inspections and SHM sensors. One limitation identified through this case study was the lack of research on occurrence probabilities of in-depth basic events, such as those related to corrosion. More research on occurrence probabilities for initiating basic events would be beneficial to the success of bridge risk analysis through FTA.

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