Fault Tree Analysis of Schoharie Creek Bridge Collapse

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Abstract: The United States has witnessed several bridge collapses that have resulted in human fatalities. One such failure was the Schoharie Creek Bridge (1987), which motivated the improvement of bridge management policies and procedures. This paper offers a detailed review of the events that resulted in this bridge failure through the use of fault tree analysis. A fault tree is a graphical depiction of the various failure paths that lead to an undesirable outcome. The tree presented considers a host of catastrophic events ranging from vessel collision to fire. Fault trees also provide quantitative assessment and comparison of different failure mechanisms. The results of this analysis present scour as the source of the collapse of this bridge, which was in reality the root cause. Knowledge of the vulnerabilities particular to a bridge aids in the management of similar bridge types, allowing focus upon critical aspects. Recognition of historical bridge failures offers awareness to current bridge engineers and managers that aids in the decision making that promotes public safety and structure preservation. Lessons learned will help avoid similar catastrophic failures in the future.

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Introduction

Throughout history, catastrophic bridge failures have occurred resulting in the loss of human life, disruption of commerce, and enormous repair costs. Bridges are important links in our nation's infrastructure that must be protected in order to provide safety and serviceability for the public. Bridge designs should continually improve as well as the maintenance and rehabilitation programs intended to protect these valuable assets. The in-depth review of historical bridge failures offers valuable knowledge and insight to the structural engineers and bridge managers of today.

This paper is a presentation of the historic bridge failure of the Schoharie Creek Bridge using fault tree analysis. In addition to visually simplifying the bridge as a system, a fault tree sets forth logical interrelationships that qualitatively describe the different failure paths for comparative analysis. The fault tree is developed and evaluated for alternative failure scenarios.

Fault Tree Model of Bridge Collapse

A fault tree provides an approach to modeling a complex system (in this case the system is a bridge) that supplies a method of evaluating the system-level failure probability considering the interaction of different system components (Sianipar and Adams 1997; Johnson 1999). It identifies failure paths and critical elements, such as a pier foundation. A fault tree advantage is its ability to unveil logical interrelationships of the bridge system through graphical depiction and Boolean algebra. The bridge can be modeled in its entirety, including element interactions, redundancy, deterioration mechanisms such as corrosion and fatigue, and environmental factors. Table 1 provides an explanation of the symbols used in a fault tree.

Knowledge of critical failure paths is useful for bridge management needs and objectives. Information on the relative importance of failure mechanisms can provide bridge designers with physical reasoning to improve rehabilitation of current bridges and designs of future bridges. Furthermore, awareness of failure-prone elements is important to field inspectors when evaluating the condition of bridges. Condition assessment information provided by a fault tree can also be utilized when making prioritizing decisions of maintenance for a bridge population.

While the failure of the Schoharie Creek Bridge occurred quite suddenly, the deterioration that led to the catastrophic collapse was in no way instantaneous. The following application of fault tree analysis to the Schoharie Creek bridge failure describes the pattern of events that contributed to the deterioration that eventually led to collapse.

Schoharie Creek Bridge

The Schoharie Creek Bridge carried the New York State Thruway (I-90) over Schoharie Creek, a major tributary of the Mohawk River located in central New York. Constructed in the years 1953 through 1955, the bridge consisted of five simply supported spans reaching a total length of approximately 540 ft (165 m). Four lanes of traffic, two in each direction, were carried approximately 80 ft (24 m) above the water, as shown in Fig. 1.

The superstructure of each bridge span was made up of two steel girders and a system of floor beams, while the substructure consisted of four concrete piers and two abutments. Each pier was made up of two columns connected at the top by a tie beam. The

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Table 1. Symbolic Notation Used in Fault Trees

Symbol	Name	Usage
	Event	Top and Intermediate positions
	Basic Event	Bottom positions
	Condition Event	Used with INHIBIT Gate
	Undeveloped Event	Fault expanded no further
	OR Gate	Union of two or more events
	AND Gate	Intersection of two or more events
	INHIBIT Gate	Conditional AND gate

bottom of the columns framed into a concrete plinth on top of a shallow spread footing (Fig. 2).

Thirty-two years after the bridge was in service, on April 5, 1987, the bridge collapsed during a severe flood, taking 10 lives. Pier 3 failed due to a scour deterioration mechanism; the riprap around the footing provided inadequate protection against the stream bed erosion, and the plinth and the footing fractured in tension, causing the pier to collapse. The collapse of spans 3 and 4 immediately followed and Span 2 collapsed within a few hours. Fig. 3 is a photograph of the bridge collapse.

Fault Tree Model of Schoharie Creek Bridge

The objective of this paper is to demonstrate the use of fault tree analysis applied to a bridge. The tree is implemented as a prognostic model created at the design stage; in other words, the Schoharie Creek Bridge has been designed and the tree troubleshoots all possible events that could cause the bridge to collapse. A fault tree represents one point in time, which happens to be the time of collapse for this bridge, or more specifically the conditions of the Schoharie Creek Bridge at 32 years of service. In summary, this tree is created at the design stage to surmise how it would fail 32 years later.

The fault tree assumes the bridge to be constructed according to design and specifications. It also assumes that no major repairs occur and no inspections or maintenance are performed over the 32 years of service. Currently, bridges are routinely inspected, but over the service life of the Schoharie Creek Bridge, inspection standards were lacking and often nonexistent. The fault tree takes this into account and considers the above-described worst-case scenario.

The fault tree is established with the top event: *Collapse of the Schoharie Creek Bridge at* 32 *Years Service*, as shown in Fig. 4 and in more detail in Fig. 5. Each fault tree event must be defined in terms of a *what* and *when* description (Haasl et al. 1981). Therefore, for this event, the *what* is the collapse of the Schoharie Creek Bridge, specifically, the collapse of a portion of the bridge rendering it impassable. The *when* is 32 years service, which is the age of the bridge at the time of collapse. Once the top event is defined, it is categorized as a system fault, prompting the identification of its causes.

The bridge as a system is mainly a superstructure supported by a substructure. Dissecting the top event in terms of the superstructure, the collapse of the bridge is more specifically defined as the collapse of any one of the superstructure spans, as shown in Fig. 4. The events are the collapses of each of the simply supported spans that make up the superstructure. There are five specific events: *Collapse of the Superstructure Span X at* 32 *Years Service*, where $X=1$ to 5, representing the five spans, shown in Fig. 4. These events are considered independent, a reasonable assumption given that each span is simply supported rather than continuous. The superstructure events or input events are joined through an OR gate to the output event *Collapse of the Schoharie Creek Bridge at* 32 *Years Service*. The OR gate defines that the collapse of the bridge occurs as the collapse of any one of the five spans. Note that causality is never passed through an OR gate, and the input events are re-expressions of the output events more specifically defined (Haasl et al. 1981).

The following discussion describes the elements of the fault tree design for the Schoharie Creek Bridge. Due to space constraints and the overarching complexity of the tree, the tree in its entirety is not provided in this paper. Rather, the development of the tree is focused on and limited to the collapse of the superstructure span 3, the actual span that fell. Fig. 5 and Table 2 may be referenced as visual aids in the following descriptive discussion.

The fault of the collapse of the superstructure span 3 is also a system fault, considering that the superstructure span is its own subsystem made up of a concrete deck, two main supporting girders, and a system of floor beams. The interest now is the cause of collapse of the subsystem and its subsequent components. Certainly the collapse of the supporting elements, abutment or pier, would result in a collapse of the superstructure span. Bearings could also fail to keep the superstructure in place during a cata-

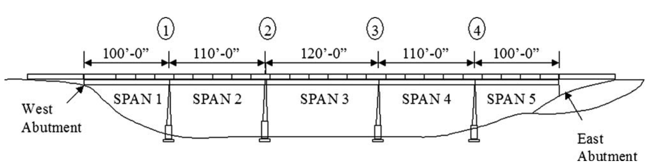

Fig. 1. Elevation of Schoharie Creek Bridge (WJE/MRCE 1987)

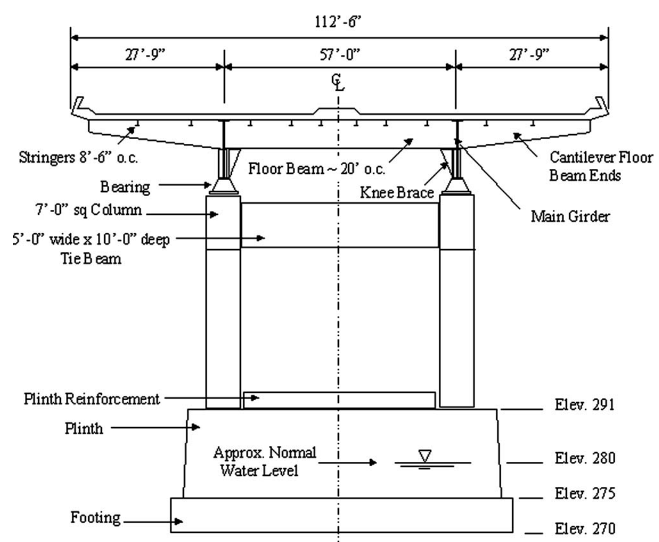

Fig. 2. Pier of Schoharie Creek Bridge (WJE/MRCE 1987)

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Fig. 3. Collapse of Schoharie Creek Bridge [Photo courtesy of Schenectady Gazette (1902)]

strophic event such as a vessel collision. Imagine a large ship that does not meet the vertical clearance restrictions hitting the superstructure midspan. The lateral force of the collision may overcome the anchoring effects of the bearings and the span is pushed off the piers. Keep in mind, the tree is created at the design stage and attempts to account for all possible events explaining collapse of the bridge.

The fault could also be within the superstructure subsystem. The superstructure is made up of two steel girders and a system of floor beams that support a concrete deck. The failure of one of the steel girders could cause the collapse of the superstructure span due to the inability of the remaining beam to support the loads. On the other hand, if the system of floor beams failed, the main beams would still support the span and it is also not plausible that the concrete deck could fail in such a way that would cause the superstructure span to collapse. Therefore, the failures of the floor beam system and the concrete deck are not included within the tree. This leaves the event of the collapse of either of the two main girders as the fault that lies within the superstructure subsystem. The superstructure lacks redundancy because of the fact that there are only two main girders; and this lack of redundancy is reflected in the fault tree.

The collapse of a main girder is considered a component failure. Component failures are further defined through primary and secondary modes of failure. As defined in the *Fault Tree Handbook* (Haasl et al. 1981), a primary fault is an internal fault of a component that occurs in an environment for which the component is qualified. A secondary fault is an external fault of a component that occurs in an environment for which it has not been qualified (Haasl et al. 1981).

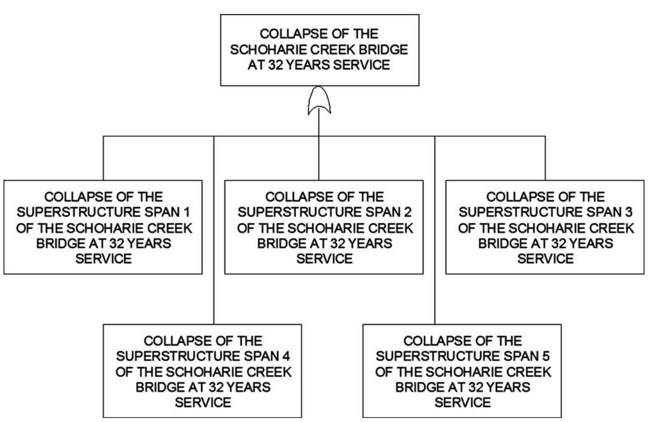

Fig. 4. Fault tree of collapse of Schoharie Creek Bridge: top event and top tier

In the determination of the primary fault leading to the collapse of a main girder, the following question can be posed: *Why would it collapse through fault of its own under circumstances for which it was designed?* Deterioration is expected, although design standards try to ensure that a component will resist deterioration for an amount of time. The absence of adequate inspection and maintenance allows a level of deterioration that could compromise the component. The types of deterioration that could affect a steel beam and cause its collapse are corrosion and fatigue. Corrosion is a deterioration mechanism caused by environmental factors such as exposure to water and deicing salts and results in a lower cross-sectional area, which compromises the strength of the girder and makes it vulnerable to local buckling and failure. Fatigue is deterioration typical of steel members due to the cyclic loading of traffic, which results in sudden brittle failure.

External or secondary events could cause the collapse of a main girder. For example, during an extreme heat event, when the temperature is above 900°, there is a major loss in strength (AASHTO 2003) leading to collapse of the girder. A scenario of this situation is a marine vessel engulfed in flames located below the bridge. Another external or secondary fault event is a vessel collision into a girder with such force that there is brittle fracture and it fails. Such a vessel could be an airplane crashing into the superstructure or a ship that surpasses the height clearance beneath the bridge. A third secondary event that could cause the collapse of a main girder is an overload such as a truck carrying an illegal nonpermitted load. In summary, the secondary fault events of a main girder considered in the tree account for extreme heat, vessel collision, and overload.

Revisiting the event of the bearings failing to keep the superstructure in place, we look at the primary cause as a lateral force that exceeds a critical magnitude and causes the superstructure to slip off. One source of such an extreme lateral force could be a high wind or waves in the event of a storm such as a hurricane. A vessel collision, either marine or aeronautical, could also hit the superstructure with a critical amount of lateral force. In construction of the fault tree, these events are set up with an inhibit gate and a conditional ellipse specifying that the incurred lateral forces are of critical magnitude in order to *push* the superstructure off the bearings.

Abutment or pier failure can lead to superstructure collapse. These are considered component failures, dividing the faults into primary and secondary categories. Looking into the pier failure as a primary fault, *how could it fail in such a way as to cause the collapse of the superstructure span it supports?* A fault internal to the pier is the deterioration of the pier foundation material leading to vertical movement (downward) of the pier, disrupting the balance of the superstructure to such a degree that its collapse is possible.

The sources of a secondary fault of the pier result in movement of the pier: vertical, lateral, and rotational. One source of both vertical and rotational pier movement capable of resulting in the collapse of the supported superstructure is soil-bearing failure. The occurrence of an earthquake could cause both vertical and lateral movement of the pier. Also, a marine collision could be the source of lateral or rotational movement. Scour of the pier foundation could result in vertical and rotational movement of the pier through the undermining of the foundation support, a shallow

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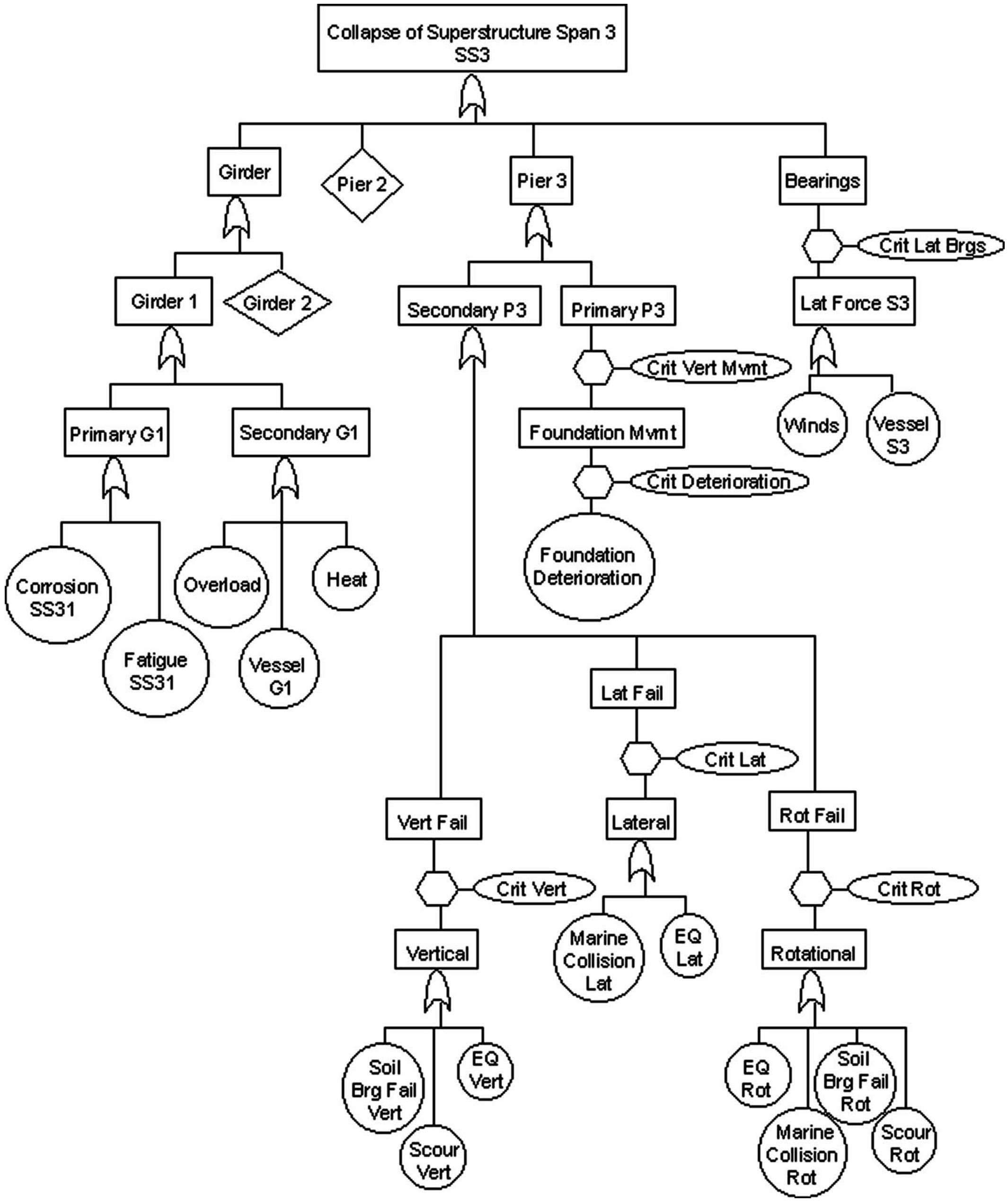

Fig. 5. Fault tree branch: collapse of superstructure Span 3

spread footing in this case. Scour is defined as the removal of material from streambed or embankment as a result of erosive action of streamflow (AASHTO 2003).

To summarize, a fault tree of the collapse of the Schoharie Creek Bridge is presented in this section. It is constructed from the point of view of the bridge engineers at the design phase in order to consider all possible modes of collapse of the bridge. The fault tree represents the point in time of the collapse that occurred when the bridge was 32 years in service, and the fault tree reflects the worst-case scenario through the assumption of no inspection or repair occurring over the life of the bridge. This fault tree of the collapse of Schoharie Creek Bridge qualitatively explains the possible modes of failure in an exhaustive fashion, down to the level of detail of the basic events as the possible sources of failure. Evaluation of the fault tree leads to probable collapse failure modes, presented in the next section.

Evaluation of Fault Tree

The fault tree of the collapse of the Schoharie Creek Bridge presented in this paper is evaluated in order to show the weaknesses of the bridge system through the revelation of failure paths and critical elements. Each logic gate is expressed as an equation of Boolean algebra. In Fig. 4, the OR gate along with the input and output events is shown in engineering symbolism:

$$T = SS1 + SS2 + SS3 + SS4 + SS5 \tag{1}$$

where T=Collapse of the Schoharie Creek Bridge at 32 Years Service; SS1=Collapse of the Superstructure Span 1 of the Schoharie Creek Bridge at 32 Years Service; SS2= Collapse of the Superstructure Span 2 of the Schoharie Creek Bridge at 32 Years Service; SS3=Collapse of the Superstructure Span 3 of

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Table 2. Event Descriptions for Collapse of Superstructure Span 3 Fault Tree Branch

Event	Description
Bearings	Collapse of the superstructure Span 3 due to failure of bearings to hold superstructure Span 3 in place on day of collapse
Corrosion SS31	Collapse of the superstructure Span 3 due to 32 years of corrosion of Main Girder 1
Critical deterioration	Amount of deterioration enough to cause vertical movement Pier 3
Critical lateral	Lateral movement of Pier 3 enough to cause collapse of superstructure Span 3 or 4
Critical lateral bearings	Lateral force > critical lateral force for bearing failure (Span 3)
Critical rotation	Rotational movement of Pier 3 enough to cause collapse of superstructure Span 3 or 4
Critical vertical	Vertical movement of Pier 3 large enough to cause collapse of superstructure Span 3 or 4
Critical vertical movement	Vertical movement large enough to cause collapse of Span 3 or 4 of superstructure
EQ lateral	Lateral movement of supporting Pier 3 at 32 years service due to earthquake on day of collapse
EQ rotation	Rotational movement of supporting Pier 3 at 32 years service due to eq. on day of collapse
EQ vertical	Vertical movement of supporting Pier 3 at 32 years service due to earthquake on day of collapse
Fatigue SS31	Collapse of the superstructure Span 3 due to 32 years of fatigue of Main Girder 1
Foundation deterioration	Deterioration of Pier 3 foundation material at 32 years service
Foundation movement	Vertical movement of supporting Pier 3 at 32 years. service due to deterioration of pier found material
Girder	Collapse of the superstructure Span 3 due to collapse of Main Girder at 32 years service
Girder 1	Collapse of the superstructure Span 3 due to collapse of Main Girder 1 at 32 years service
Girder 2	Collapse of the superstructure Span 3 due to collapse of Main Girder 2 at 32 years service
Heat	Extreme heat event in vicinity of bridge on day of collapse
Lateral failure	Failure of supporting Pier 3 at 32 years service due to lateral movement
Lateral force S3	Lateral force applied to superstructure Span 3
Lateral	Lateral movement of supporting Pier 3 at 32 years service
Marine collision lateral	Lateral movement of supporting Pier 3 at 32 years service due to marine collision
Marine collision rotation	Rotational movement of supporting Pier 3 at 32 years. service due to marine collision on day of collapse
Overload	Collapse of Main Girder 1 of Span 3 during overload of critical magnitude
Pier 2	Collapse of the superstructure Span 3 due to failure of supporting Pier 3 at 32 years service
Pier 3	Collapse of the superstructure Span 3 due to failure of supporting Pier 2 at 32 years service
Primary G1	Collapse of the superstructure Span 3 due to collapse of Main Girder 1 at 32 years service (primary fault)
Primary P3	Failure of supporting Pier 3 at 32 years service (primary fault)
Rot failure	Failure of supporting Pier 3 at 32 years service due to rotational movement
Rotational	Rotational movement of supporting Pier 3 at 32 years. service
Scour rotation	Rotational movement of supporting Pier 3 at 32 years service due to scour of pier foundation
Scour vertical	Vertical movement of supporting Pier 3 at 32 years service due to scour of pier foundation
Secondary G1	Collapse of the superstructure Span 3 due to collapse of Main Girder 1 at 32 years. service (secondary fault)
Secondary P3	Failure of supporting Pier 3 at 32 years Service (Secondary Fault)
Soil bearing failure rotation	Rotational movement of supporting Pier 3 at 32 years service due to soil bearing failure
Soil bearing failure vertical	Vertical movement of supporting Pier 3 at 32 years service due to soil bearing failure
SS3	Collapse of the superstructure Span 3 of the Schoharie Creek Bridge at 32 years service
Vertical failure	Failure of supporting pier at 32 years service due to vertical movement
Vertical	Vertical movement of supporting Pier 3 at 32 years service
Vessel G1	Collapse of main girder during vessel collision having a critical amount of force (Span 3)
Vessel S3	Lateral force from collision of vessel into superstructure Span 3
Winds	Lateral force from storm applied to superstructure Span 3

the Schoharie Creek Bridge at 32 Years Service; SS4=Collapse of the Superstructure Span 4 of the Schoharie Creek Bridge at 32 Years Service; and SS5=Collapse of the Superstructure Span 5 of the Schoharie Creek Bridge at 32 Years Service.

The same equation in mathematical symbolism is

$$T = \mathrm{SS1} \cup \mathrm{SS2} \cup \mathrm{SS3} \cup \mathrm{SS4} \cup \mathrm{SS5} \tag{2}$$

The evaluation of the fault tree begins at the top with this initial equation. Descending down the tree, each event is substituted with a more detailed combination of events. The ultimate goal is to express the top event as combinations of the basic events, often referred to as cut sets. Formally, cut sets are the combinations of events, both basic and intermediate, that result in the failure event, in other words, the failure paths. Minimal cut sets are those cut sets that include the least amount of events. For this tree, there are over 150 cut sets. The cut sets that are made up of only one element are considered the most critical failure paths.

In this tree, for example, some of the single cut sets represent bridge collapse due to overload, vessel collision, and fire. These events are critical in that failure is catastrophic and instantaneous. However, some cut sets that are larger, containing two or three events, may be significant, such as the cut set that represents

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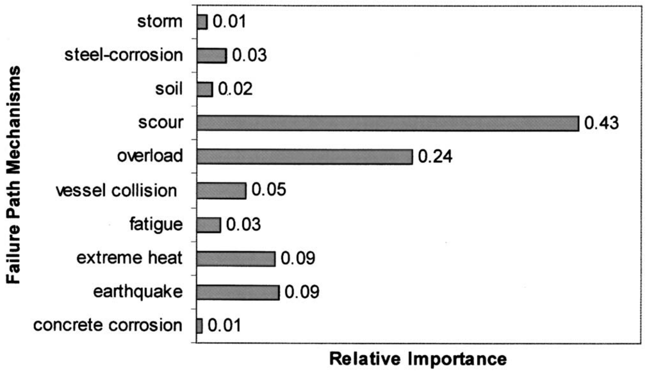

Fig. 6. Relative importance of failure path mechanisms

scour, the actual failure path of the bridge. This brings to light the limitations of the qualitative aspect of a fault tree. Although it is useful in showing the various failure combinations graphically, the vulnerable aspects of the bridge are only properly unveiled with an additional numerical evaluation involving the probability values of the basic events. Once input into the tree, the Boolean algebra is executed, offering results such as probability of failure of the top event and relative importance ranking of the cut sets.

In this tree, the probabilities of the basic events were obtained from a statistical study on bridge failures in the United States completed by Wardhana and Hadipriono (2003). The study is based on the modes of failure of over 500 bridges over a period of 12 years (1989–2000). The information was compiled from several sources, including engineering publications, Web sites, and communications with a number of state departments of transportation. One portion of the study classified the primary causes of failure of each of the 503 bridges into 23 categories, including scour, earthquake, and overload, even including such rare events as train collision. The percentages of bridges that fell into each category were also provided. The probabilities of the basic events of this fault tree were taken directly from these percentages. Moving up the tree, the conditional events were assumed to occur with certainty in order to consider the worst-case scenario. In other words, if the conditioning event required that the lateral force of a collision be of a certain critical magnitude, it was assumed that this condition was satisfied with 100% probability.

The Boolean algebra of the tree was executed taking into account the common cause effect. In other words, an earthquake may be the source of a number of failure paths, and this must be accounted for so that the failure probabilities are not erroneously inflated. Only one branch of the tree representing the collapse of the superstructure span 3 was focused on and included in the calculations, in order to maintain workability in the analysis. The probability of *Collapse of the Superstructure Span 3 of the Schoharie Creek Bridge at* 32 *Years Service* is 36%, considering all modes of failure. This probability of failure is unacceptable; according to the U.S. Army Corp of Engineers, failure probabilities above the threshold of 7% require emergency action (Johnson 1999).

Relative importance ranking of the cut sets reveals the critical failure path mechanisms. The results plotted in Fig. 6 show that the greatest contributor to the collapse of the superstructure span 3 was the minimal cut set representing scour. Therefore, the fault tree model along with the input data support the conclusion that the Schoharie Creek Bridge failed due to scour.

The numerical results offered by this fault tree indicate that a bridge design is prone to failure and must be improved. The tree points out which elements are more susceptible than others: for example, the pier foundations in this case. Piles as opposed to shallow footings would remove the vulnerability of the pier foundations to scour. Overload is also identified by the tree as a possible failure event, pointing to the failure of one of the two main girders. A common-sense design solution would be to incorporate more redundancy into the bridge by adding more girders. Beyond the design stage, these results point out that scour is a concern, prompting regular underwater inspections.

Concluding Remarks

The fault tree of the catastrophic failure of Schoharie Creek Bridge in which lives were lost is presented and highlights the susceptibility of the pier foundations. The fault tree describes the bridge as a system of interacting components. It graphically depicts deterioration mechanisms and their triggers, allowing one to trace these to the contributing sources of a potential collapse. The fault tree analysis can identify critical elements for inspection in bridge systems. The importance of accurate inspection of critical elements is evident. The fault trees also make clear the lack of redundancy in design of bridges. This imposition of a thought process related to redundancy helps engineers adequately retrofit existing bridges and improve the design of new bridges. Knowledge of the process of bridge deterioration and its system-level impact allows the bridge manager to make effective decisions in prioritizing maintenance plans.

In ongoing research, the writers have developed the branch of the tree that represents scour, the mechanism by which the bridge failed. The level of detail includes deterioration mechanisms such as long-term scour, contraction scour, and local scour. These are further developed to consider their sources, such as natural erosion and its acceleration due to river modification, changes in channel alignment, changes in channel dimensions, and urbanization of the watershed. Also considered, are acceleration of flow due to contraction of waterway, natural (natural stream construction, formation of sediment deposits, heavy vegetation) or manmade (excessive number of piers or other obstructions).

For reasons of space constraints, the development of the scour branch is introduced in discussion only. Future research could continue the growth of this branch. The value of expanding the tree qualitatively is realized only in exercising the quantitative aspects also. This would involve obtaining the basic numerical probabilities particular to this bridge and incorporating analytical equations modeling scour deterioration. Results from a model such as this could be compared and calibrated with available statistical data. This could prove to be a powerful tool that could be incorporated into existing bridge management software to aid in the condition assessment of bridges on both an individual and population level.

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