Fault-Tree Model of Bridge Element Deterioration Due to Interaction

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Abstract: Bridge engineers and bridge inspectors recognize that deterioration of one element influences the deterioration of another. The effect of this phenomenon may be critical if it increases the deterioration rate of the affected elements. The phenomenon is known as element interaction. The consequences of element interaction can help to explain why elements of the same type have varying deterioration rates. No practical model exists for modeling element interaction. This paper presents the use of a fault tree for qualitative and quantitative evaluation of element interaction phenomena. The fault-tree results can be used to better assess the deterioration rate and improve deterioration prediction of an element. An example of the fault-tree model for accelerated deterioration of concrete bridge decks is presented. The fault-tree model is not a deterioration model, but can be used to focus on mitigating accelerated element deterioration by certain maintenance or repair actions. Systematic implementation of the fault-tree approach presented herein must be preceded by field verification.

INTRODUCTION

This paper focuses on modeling bridge deterioration in terms of element conditions that can be directly correlated with particular bridge maintenance actions. Age is not a parameter of this model. Although age is a significant parameter in most bridge deterioration models, there appears to be little or no correlation between average age of the bridges and the percentage of deficient spans in a particular state (Dunker and Rabbat 1993). Instead there is correlation between the total miles of bridges in a state and the percentage of deficient spans. Bridge deterioration problems are related more to maintenance practices than to age.

Bridges have three major components: deck, superstructure, and substructure. These components comprise one or more elements. Elements, such as the deck, girders, joints, bearings, etc., are identified because they are important from a structural, user, or cost standpoint (*Federal* 1993). Different bridges may comprise different sets of elements. Bridges with similar elements can have different quantities of them.

Bridge inspectors have observed that deterioration of one bridge element can accelerate the deterioration of certain other elements (Beaty memorandum, January 9, 1995). For example, the deterioration of a concrete deck accelerates if its bearings do not function properly. If the bearings freeze due to corrosion, the deck is subjected to expansion and contraction stresses that cause cracking.

Deterioration due to element interaction is the contribution to the overall deterioration of a bridge element due to the condition of another element. Most of the existing deterioration models neglect deterioration due to element interaction. Existing models consider the deterioration of each element as being independent. New network-level bridge management system (BMS) models such as PONTIS (Golabi et al. 1993) uses environment levels that can be adjusted to account for element interaction. However, the environment states do not explain the causes and mechanism leading to element interaction.

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The scope of interacting elements and the intensities of these interactions are not easily measured. Knowledge about element interactions can lead to a better assessment of deterioration rates, which in turn improves deterioration predictions. This paper introduces the fault-tree method to identify, represent, and quantify the occurrence of element interaction. In addition, the fault-tree method can lead to discovery of interactions that otherwise may not be recognized as causes of accelerated element deterioration.

This paper begins with a presentation of interaction phenomena in the deterioration of concrete bridge decks. Then the role of interaction in current deterioration models is described. In particular the limitation and suitability of using environment states in a network-level BMS are discussed. Next, the fault-tree approach and its use to identify, represent, and measure element interaction is introduced. Finally, the implementation and development of a fault tree for modeling element interactions is presented through an example for accelerated deterioration of concrete bridge decks.

INTERACTION PHENOMENA IN BRIDGE DETERIORATION

Bridge elements deteriorate over time. All elements are physically interconnected while each of them serves a specific function. The interconnectedness of these elements can be a source of problems if one of the elements malfunctions. The term malfunction here means failure to operate as specified in the design. Element interaction occurs when the deterioration of a malfunctioning element accelerates the deterioration of another.

To illustrate some phenomena of element interactions observed in the field, the following examples describe interaction between bridge deck and superstructure elements, e.g., girders, joints, and bearings (Beaty memorandum, January 9, 1995):

- Deck joints, bearings, and decks: Debris lodged in the joints prevents normal expansion and contraction. Traffic impacts tear the joints and cause leakage of salt and dirty water. Intrusion of chloride enables water and oxygen to attack the steel, as indicated by the formation of iron oxide (rust), and in turn advances the corrosion deterioration of the bearings. Bearings frozen by corrosion resist horizontal deck movement and, thus, increase the deterioration rate of the deck.
- Decks and girders: Full-depth transverse floor cracks and longitudinal construction joints may leak salt water onto the girders below. The deterioration mechanism in steel-

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girder bridges is capacity loss due to corrosion (Kayser and Nowak 1989).
- Deck joints, girders, and bearings: Leaking deck expansion joints allow salt water seepage that, subsequently, corrodes the girder ends and the steel bearings located under the joints.

The interaction between decks, joints, and bearings provides an example for the fault-tree model presented later in this paper. Here, the physical mechanisms are described.

The primary purpose of a bridge deck is to provide a roadway for the passing traffic. The function of a bridge deck is to distribute traffic and deck weight loads to the superstructure elements. Several events can lead to deterioration and malfunction of a concrete bridge deck

- Traffic causes wear, abrasion, and impact damage to concrete bridge decks.
- The deck is exposed to damaging environmental factors such as seawater spray, freeze/thaw cycles, moisture from rain and snow, and deicing chemicals.
- Poor quality construction concrete may experience damage (spalling and crushing) around bearing and shear areas.
- Poor design and construction deficiencies may cause flexure cracks in the concrete deck. Flexure cracks are vertical and start in the maximum tension zone. Flexure cracks may occur on the top deck surface over the supports and on the bottom between the support of the slab where flexure stress is greatest. Transverse flexure cracks may occur on the top and bottom of the deck in negative moment regions of the superstructure.

Scaling, delamination, and spalling are the evidence of deck deterioration. Scaling is the gradual and continued loss of surface mortar and aggregate over an area in the deck. Delamination is the separation of layers of concrete near the top layer of reinforcing steel. Spalling is a depression in the concrete as a result of separation and removal of a portion of the surface concrete.

The primary function of deck joints is to accommodate the expansion and contraction of the deck. Deck joints also fill the gap between the deck section and the abutment backwall and provide a smooth transition from the approach roadway to the bridge deck. Presumably, the joints must be able to withstand extreme weather conditions without compromising the ride quality across the bridge.

Malfunctioning deck joints are often related to problems elsewhere on the bridge (*Bridge* 1991). If the deck joints malfunction, the deck, girders, and steel bearings may be affected. Certain events that may cause the deck joints to malfunction occur independently or in combinations

- Weather, traffic, snow-plow blades, and debris may tear the joint seals, pull out anchorages, or remove the seals altogether. Damage to seals causes leaks.
- Accumulation of dirt and debris lodged in the joint may prevent normal expansion and contraction, causing cracking of the deck.
- Placement of new pavement over the deck joints may affect the ability of the joints to function properly. Transverse cracks in the pavement are the evidence of this problem.
- Corrosion in joint anchorage devices may cause the deck joints to malfunction.

Bearing elements are part of superstructure elements and provide the connection to the substructure. Three primary functions of bridge bearings are to transmit all loads from the superstructure to the substructure, to permit longitudinal movement of the superstructure due to thermal expansion and contraction, and to allow rotation caused by dead-load and live-load deflection (*Bridge* 1991). Fixed bearings do not allow translation of the superstructure. Expansion bearings do allow longitudinal movement. Both fixed and expansion bearings permit rotation. The following events that cause malfunction of the bearings occur by themselves or in combinations:

- Wearing of bearing elements
- Settlement of bearing supports
- Leakage of dirty or salty water
- Loosening or absence of fasteners

The purpose of a drainage system is to remove water and all hazards associated with it from the structure. Therefore the drainage serviceability and conditions are important because drainage system problems can eventually lead to structural problems. The following events, by themselves or in combinations, cause drainage malfunctions:

- Grates filling with debris
- Clogging of deck drains and inlets
- Disconnection or splitting of outlet pipes

INTERACTION MODELING IN BMS

In a BMS a deterioration model is a prediction technique for evaluating present and future bridge maintenance requirements. A deterioration model is a mathematical formulation that describes deterioration behavior based on historical and current conditions.

Numerous bridge deterioration models have been developed (Busa et al. 1985; Hyman et al. 1983; Jiang et al. 1988; Jiang and Sinha 1989; Kayser and Nowak 1989; Sobanjo 1993; West et al. 1989). These models do not consider element interactions. Instead, for simplicity, these models assume that elements deteriorate independently. Other models for highway pavements account for different interacting deterioration processes on the surface layer. The models consider the interaction between several distress types and its effect on pavement deterioration (Ben-Akiva and Ramaswamy 1993; Madanat et al. 1995).

The deterioration of a bridge element is partially determined by external environmental factors such as traffic volumes, traffic loads, and operating practice. Accordingly the deterioration of an element depends on its environment level. For example, a reinforced concrete bridge deck deteriorates faster under high traffic volumes, heavy loads, or exposure to deicing chemicals. The higher the level, the higher the deterioration rate. The four standard environment levels defined for the PONTIS BMS are (Cambridge 1995) as follows:

1. Benign: no environmental condition affecting deterioration
2. Low: environmental conditions create no adverse impacts or are mitigated by past nonmaintenance actions or highly effective protective systems
3. Moderate: typical level of environmental influence on deterioration
4. Severe: environmental factors contribute to rapid deterioration; protective systems are not in place or are ineffective

The deterioration model in the PONTIS BMS accounts for element interaction through the use of environment levels (Golabi et al. 1993). The analyst can assign an affected ele-

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ment into one environment level higher than defined in the foregoing in an attempt to increase its deterioration rate due to element interaction. Environment levels may not adequately model element interaction for the following three reasons:

1. Environment levels are determined by measuring external random factors such as traffic volume and load. However, the deterioration mechanisms of element interactions may be due to internal factors, such as excessive corrosion of another element.
2. Environment levels are insufficient if they are already exhausted to accommodate the effect of external factors. For example, consider an unprotected bridge deck element located on an interstate highway with average daily traffic (ADT) of more than 1,000 vehicles. The environment level is 4. If this unprotected deck element interacts with the deck joints or bearings in its deterioration process, the analyst cannot increase the environment level.
3. The use of environment levels to model interactions is subjective and there are no guidelines.

This paper suggests the use of fault-tree method to model element interaction. A fault tree models the mechanisms of element interaction. The fault-tree representation of element interaction leads to determining the succession of events that result in accelerated deterioration. The qualitative results of fault-tree analysis can be used to enhance the effectiveness of the BMP. The quantitative results can be integrated with existing deterioration models to produce better predictions. A fault-tree model can be used in both network-level and project-level models.

FAULT TREE METHOD

Introduced in 1961 (*Launch* 1961), a fault tree is a logic diagram consisting of a top event and a structure delineating the ways in which the top event can occur (Wood 1985). The fault-tree method is a technique for acquiring and representing information about a system (Roberts et al. 1981). Accordingly the method requires a thorough understanding of the system (Barlow and Lambert 1975).

A fault-tree analysis consists of four steps: system definition, fault-tree construction, qualitative evaluation, and quantitative evaluation (Lee et al. 1985). System definition begins with the statement of a predefined undesirable event. Information pertaining to the system includes boundary conditions, operating and failure modes, and functional interconnections. In this paper the system is the element interactions that cause accelerated deterioration of a bridge element. The top event is the accelerated deterioration of an element.

After the system is defined the first task in constructing a fault-tree structure is to determine the immediate, necessary, and sufficient causes for the occurrence of the top event (Roberts et al. 1981). The causes of the top event are then treated as subevents. In turn the immediate, necessary, and sufficient causes of these subevents are determined. The procedure continues to build the tree until some limit of resolution is reached.

After a fault tree is constructed, it can be evaluated qualitatively. Qualitative evaluation reduces the tree to a logical structure in terms of specific combinations of subevents that cause the top event to occur. Qualitative results are the minimal cut sets (MCSs) that are the smallest combination of the subevents that cause the top event to occur.

Quantitative evaluation of a fault tree transforms the logical structure into an equivalent probabilistic form so that the probability of the top event can be computed from the probabilities of the subevents.

Identifying Element Interactions

There are two ways to identify interaction of bridge elements. The first is through formal knowledge acquisition from bridge experts. The second is through statistical methods such as correlation analysis. Correlation analysis of bridge inspection data will imply interaction between the suspected elements if there is a high correlation between their condition data.

Fault-tree analysis is a knowledge acquisition structure that has been extensively explored by engineers (Geymayr and Ebecken 1995). Knowledge acquisition is a process of eliciting and enumerating the knowledge of an expert in a particular domain so that this expertise can be coded (Brulé and Blount 1989). The task of acquiring knowledge from experts and transferring it into a certain representation is not easy.

There are three participants in knowledge acquisition process: the knowledge elicitor, the knowledge programmer, and the expert. Experts are people whose expertise and experience in a given domain is to be represented. Knowledge elicitors gather knowledge from experts using questionnaires or direct interviews. Knowledge programmers take the elicited knowledge and convert it into program structures and code. The experts verify the applicability and correctness of the knowledge gathered and indicate whether changes are necessary. The experts for fault-tree modeling of element interaction need a good understanding of how bridges perform and how each element functions. The experts include bridge inspectors and bridge engineers.

The elicited information obtained from the experts may be very subjective. Different experts may have different experiences and possibly give different response to the same question. Some methods such as fuzzy set theory and/or fuzzy cognitive maps (Peláez and Bowles 1995) may be employed to resolve unequal or conflicting knowledge to a representative conditional value.

Another method to determine the possible failures of the system components and its consequences is failure mode and effect analysis (FMEA) (Toola 1993). The FMEA can be accomplished by using analytical techniques such as finite element method (Davies et al. 1971; Jategaonkar et al. 1985), modal analysis (Chang et al. 1993), and structural identification. FMEA allows what-if studies to identify potential sources of failure and the effect on the system. FMEA and fault-tree analysis can complement each other with information. For example, the FMEA may ensure that the fault tree contains all basic events, and the fault-tree analysis may ensure that the failure consequences of the FMEA are appropriately represented in the tree.

Representing Element Interactions

A fault tree is a graphical technique (Berk 1995) that can be used to identify potential causes of element interactions. In a fault tree element interaction is represented by parallel and sequential combinations of events that depict the logical interrelationship of element deteriorations that result in the occurrence of accelerated deterioration of a bridge element. The general structure of the tree can be obtained by knowledge acquisition and by combinatorial analysis of all events. As a deductive method, a fault-tree structure is constructed from the top down, starting with a top event. Downward traversal of the tree identifies and determines all possible causes of the top event.

The top-down approach to construct the fault tree reduces the possibility of overlooking important information pertaining to the top event, and enables the analyst to identify and clarify all the causes involved. As construction progresses the rela-

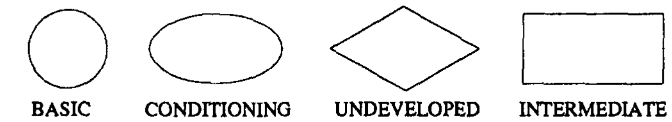

FIG. 1. Event Symbols

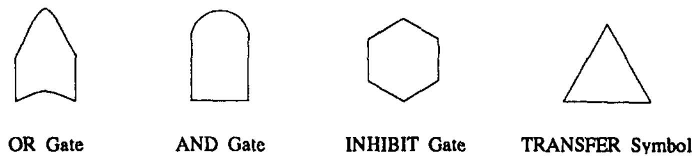

FIG. 2. Gate and Transfer Symbols

tionship between the top event and all causes becomes more evident.

Events are the essential components of a fault tree. A typical fault tree is constructed of symbols representing primary events, intermediate events, and logical combinations (gates). Primary events are causes that need no further decomposition. Fig. 1 shows the symbols for three primary events: BASIC, CONDITIONING, UNDEVELOPED (Roberts et al. 1981). A BASIC event is a simple primary event that indicates the appropriate limit of resolution has been reached. A CONDITIONING event represents a specific condition or restriction that applies to a logical combination (gate). An UNDEVELOPED event results from unavailable information or insufficient consequence. Fig. 1 also shows the symbol for an INTERMEDIATE event that results from one or more other events.

In a fault tree gates show the relationship of the causes contributing to the occurrence of an intermediate or top event. Gates permit or inhibit the passage of logic up the tree. For any gate the "higher" event is the output of the gate and the "lower" events are the inputs to the gate.

The relationship among the input events is defined by the type of gate used to connect them. Fig. 2 displays the symbols for three types of gates: OR, AND, and INHIBIT (Roberts et al. 1981). The OR gate represents a situation when at least one of the input events must occur for the output event to occur. The AND gate is used when all input events must occur for the output event to occur. The INHIBIT gate is used if an input event must occur simultaneously with a conditioning event for the output event to occur. The TRANSFER symbol in Fig. 2 is used for convenience so that the fault-tree structure can be broken into several branches depicted on different pages.

A fault-tree model represents the interactions that in the analyst's opinion lead to the occurrence of the top event. Hence the interactions shown in a fault tree are not necessarily exhaustive. In general the scope of the analysis must be carefully defined and all assumptions must be clearly stated. Failure to do so might lead to missing important input causes.

Measuring Element Interactions

Element interactions that are identified and represented in a fault tree can then be measured qualitatively and quantitatively. Qualitative evaluation of a fault tree determines the minimal cut sets (MCSs). The MCSs are obtained by Boolean reduction of the fault tree. Boolean algebra models situations involving dichotomy, such as events that either occur or don't occur. The process of determining the MCSs begins with translating the events that cause element interactions into its equivalent Boolean equations. Then by using the substitution method the top event (accelerated deterioration) is expressed as an equation in terms of all the causes. The relationships among all causes are then reduced to a more simple association in terms of MCSs. The reduction process makes use of Boolean algebra rules, including commutative law, distributive law, associative law, idempotency law, and De Morgan's law.

A fault tree consists of a finite number of MCSs that are unique for that top event. Each MCS consists of a combination of specific causes. The one-component MCS represents a single cause of the top event. Likewise, the two-component MCS represents two causes that together make the top event to occur.

The MCS also indicates the importance of interaction. Generally the probabilities associated with the MCSs decrease by orders of magnitude as the size of the cut increases. The smaller the MCS the more important it is to the occurrence of the top event. Hence the double-component MCSs are more important than the triple-component MCSs, and so on. Subsequently, the list of element interactions in order of importance can be prepared. The list gives qualitative ranking on how each component contributes to the occurrence of the top event.

Once the Boolean relationships among all the events have been established and the reduced form of the fault tree has been obtained, the quantitative evaluations can be performed to determine the numerical probability of the top event. The occurrence of acceleration in element deterioration due to interaction can be measured using probabilistic or statistical techniques. Probability theory provides an analytical treatment of events that cause interactions. Algebra of probabilities, combinatorial analysis, and set theory are part of probability theory that can be used in the quantitative analysis. Statistical tools can be used to model the frequency of occurrence of events leading to interactions. The extent of interactions can be quantified with probabilistic mapping of the events and their conditionals. Conditional probabilities are used if a basic event appears in more than one MCS.

Quantitative analysis of a fault tree is bottom up following three sequential steps: determine probability of basic events, calculate probability of MCS, and compute probability of parent event. To determine the basic event probabilities, an assessment of the probability distribution profiles corresponding to each basic event parameter is needed. If no data are available the probabilities of the basic events can be obtained from the knowledge acquisition process. If enough data are available the probability distribution profile that best described the relative frequency of each basic event can be established.

The quantitative analysis yields the quantitative importance of each cut set and each basic event. The higher the probability of an MCS the more significant its contribution to the system. The quantitative importances indicate the percentage of time that the top event is caused by a particular MCS. This information can be used to direct the maintenance, repair, and rehabilitation (MR&R) actions to mitigate the occurrence of undesired top event. The probability of the top event can be incorporated to the existing element deterioration model to account for element interaction.

FAULT-TREE MODEL OF ACCELERATED CONCRETE BRIDGE DECK DETERIORATION

In this section an implementation of the fault-tree method to model element interaction leading to accelerated deterioration of concrete bridge decks is described. The implementation includes knowledge acquisition, construction of the fault-tree structure, qualitative evaluation of the MCSs, and quantitative evaluation of the top event. The fault-tree example presented here models accelerated deterioration of concrete bridge decks caused by element interaction with bearings and/or joints as observed by bridge engineers (Beaty memorandum, 1995). The linguistic description of the interaction phenomena was

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presented previously in this paper. This section describes an analytical representation of the observations.

The example is a coherent fault tree shown in Figs. 3–5 where the following basic events are indicated:

S1: Damage to areas exposed to traffic (scaling, delamination, wearing, spalls)
S2: Damage to areas exposed to drainage (general deterioration of the concrete)
S3: Damage to bearing and shear areas (crushing and spalls)
S4: Flexure cracks (top over the supports and bottom between the supports of the slab)
S5: Transverse flexure cracks (in the negative moment region of top and bottom of the slab)
S6: Worn bearing elements
S7: Loose or missing fasteners (used to attach the bearing to the support or the superstructure)
S8: Damage to joint seals
S9: Dirt accumulation (prevent normal expansion and contraction)
S10: Indiscriminate overlay
S11: High traffic volume causing settlement of the bearing support
S12: Heavy traffic load causing settlement of the bearing support
S13: Grates are filled with debris
S14: Deck drains and inlets are not of sufficient size to carry the runoff
S15: Outlet pipes are split or disconnected
S16: High traffic volume causing deficiency of joint anchorage
S17: Heavy traffic load causing deficiency of joint anchorage

A coherent fault tree assumes that each component is relevant and if one component fails the failure probability of the system increases (Barlow and Proschan 1975). Accelerated concrete

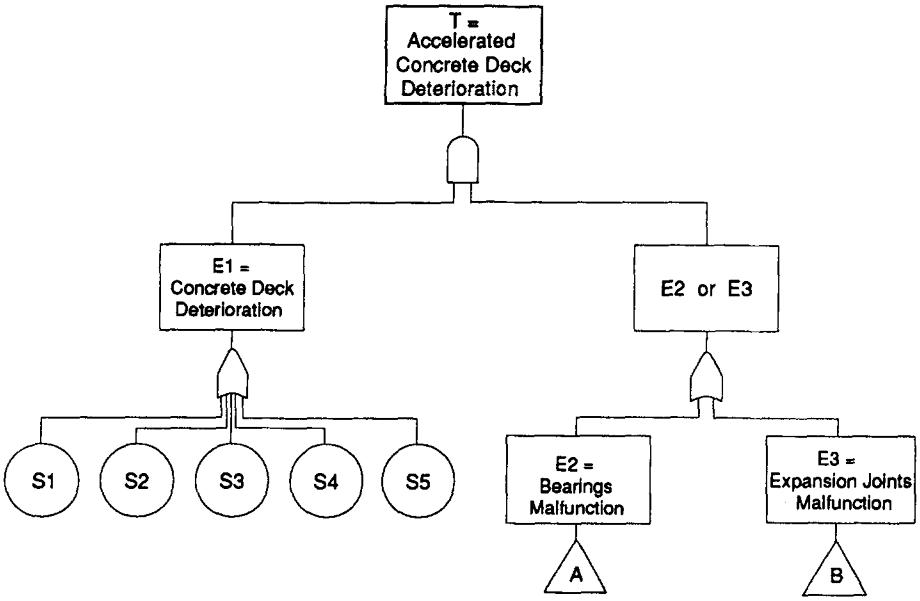

FIG. 3. Fault Tree for Accelerated Concrete Deck Deterioration

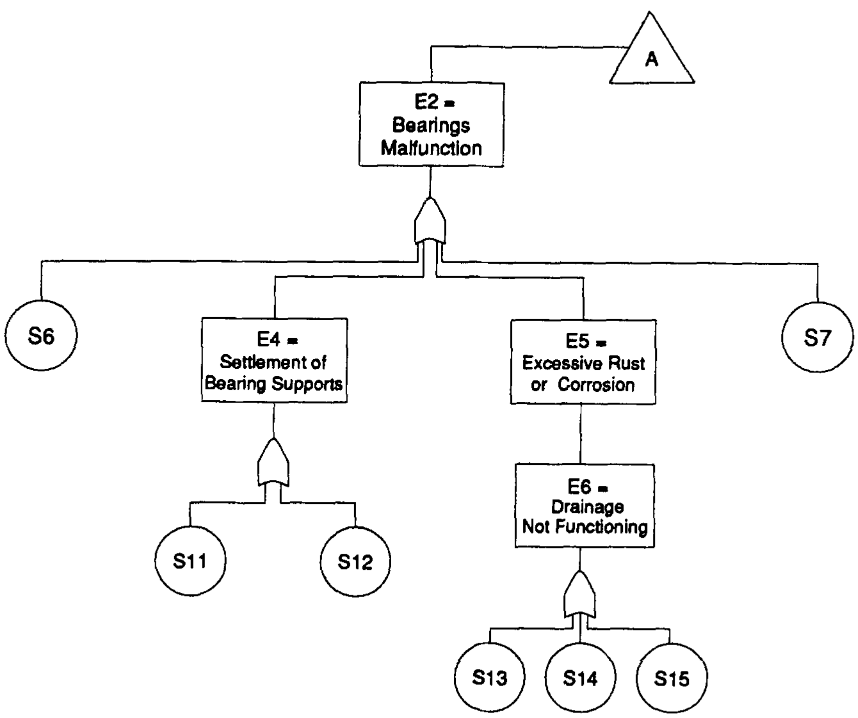

FIG. 4. Fault Tree for Malfunctioning of Concrete Deck Bearings

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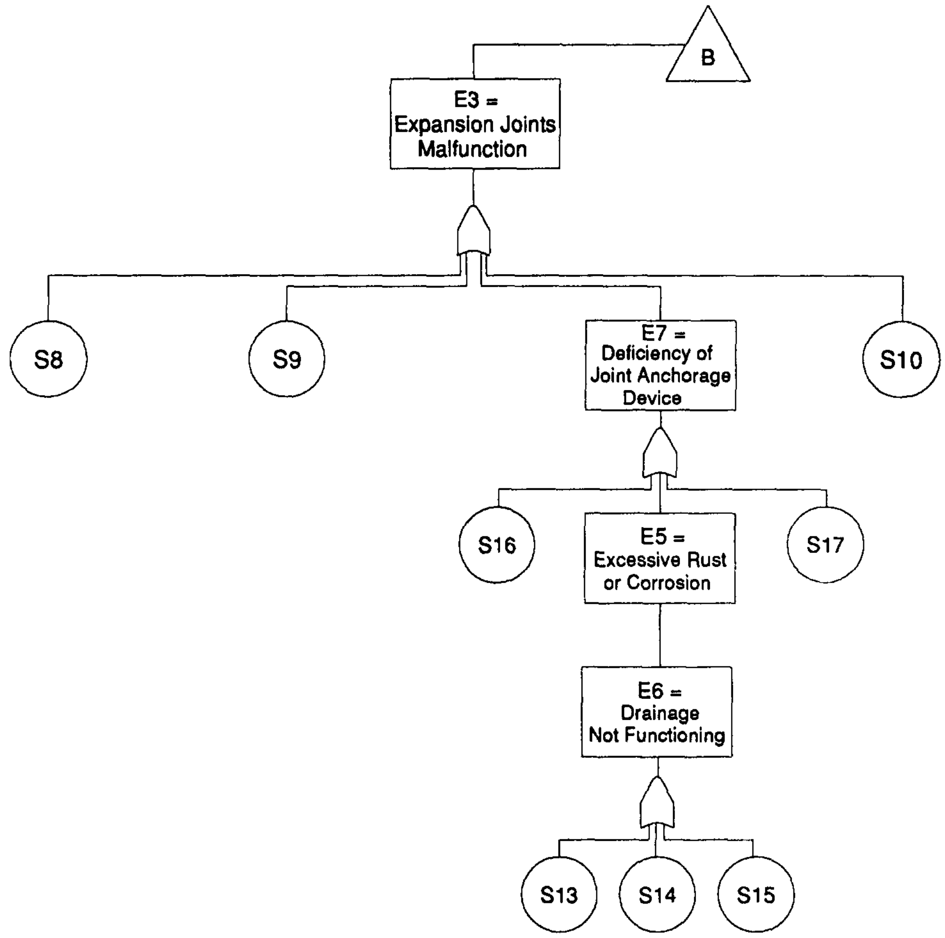

FIG. 5. Fault Tree for Malfunctioning of Concrete Deck Expansion Joints

deck deterioration is the top event. The basic events, shown in circles, are designated by an S. The intermediate events, shown in rectangles, are designated by E. Descriptions of the basic events are given in Figs. 3–5. The transfer symbols A and B link Figs. 4 and 5 with Fig. 3, respectively.

Qualitative analysis of the fault tree involves obtaining the MCSs. Computationally an OR gate represents the union of the events attached to the gate. An AND gate represents the intersection of the events attached to the gate. The fault tree of Figs. 3–5 can be written as an equivalent set of Boolean equations. Each gate in the tree has one equation.

From Fig. 3 the top event T (accelerated concrete deck deterioration) occurs if intermediate events E1 and E2 occur or if events E1 and E3 occur. Hence in the first equation that follows, T is the intersection of E1 and (E2 or E3) events. Event E1 $\cap$ E2 ($\cap$ = intersection) represents element interaction between the concrete deck and bearings. Event E1 $\cap$ E3 represents element interaction between the concrete deck and expansion joints. Similarly, events E1, E2, and E3 can be represented by their corresponding immediate causes according to the second to fourth equations that follow, respectively. Event E1 is the union ($\cup$) of basic events S1, S2, S3, S4, and S5. Event E2 is the union of events S6, E4, E5, and S7. Event E3 is expressed as the union of events S8, S9, E7, and S10. Events S1, S2, S3, S4, S5, S6, S7, S8, S9, and S10 are basic and need no further decomposition

$$T = E1 \cap (E2 \cup E3) \tag{1}$$

$$E1 = S1 \cup S2 \cup S3 \cup S4 \cup S5 \tag{2}$$

$$E2 = S6 \cup E4 \cup E5 \cup S7 \tag{3}$$

$$E3 = S8 \cup S9 \cup E7 \cup S10 \tag{4}$$

As shown in Figs. 4 and 5, events E4, E5, E6, and E7 can be further expressed in terms of basic events. The Boolean expressions for events E4, E5, E6, and E7 are given in the following:

$$E4 = S11 \cup S12 \tag{5}$$

$$E5 = E6 = S13 \cup S14 \cup S15 \tag{6}$$

$$E7 = S16 \cup E5 \cup S17 \tag{7}$$

To determine the MCSs, the right hand side of (3), (4), and (7) must be expressed in terms of basic events. Events E1, E4, E5, and E6 are already in MCS form as they contain only the basic events. Event E5 has no direct component failure and, hence, has no gate attached to it. Event E7 can be stated in MCS form by substituting (6) into (7). Then substituting (5) and (6) into (3), and (7) into (4) yield the MCSs for E2 and E3, respectively. Finally, substituting E1, E2, and E3, expressed in terms of basic events, to (1) yields the MCSs for the top event T.

$$\begin{aligned} T = {} & (S1 \cup S2 \cup S3 \cup S4 \cup S5) \\ & \cap [(S6 \cup S7 \cup S11 \cup S12 \cup S13 \cup S14 \cup S15) \\ & \cup (S8 \cup S9 \cup S10 \cup S16 \cup S17 \cup S13 \cup S14 \cup S15)] \end{aligned} \tag{8}$$

Using the distributive law and the idempotency law, (8) can be expressed in terms of the MCSs. Idempotency law states that the union or intersection of an event to itself produces the same original event. Expanding (8) produces 60 double-component MCSs for the top event T. For the top event to occur at least one of these double-component MCSs must occur. For example, as one of the 60 MCSs, (S3 $\cap$ S8) represents the

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TABLE 1. Probabilities for Accelerated Concrete Bridge Deck Deterioration

Basic event (1)	Node (2)	Probability (3)
Damage to areas exposed to traffic	S1	0.15
Damage to areas exposed to drainage	S2	0.07
Damage to bearing and shear areas	S3	0.01
Flexure cracks	S4	0.25
Transverse flexure cracks	S5	0.27
Worn bearing elements	S6	0.03
Loose or missing fasteners	S7	0.07
Damage to joint seals	S8	0.10
Dirt accumulation (prevent expansion and contraction)	S9	0.04
Indiscriminate overlay	S10	0.05
High traffic volume causing settlement of the bearing support	S11	0.03
Heavy traffic load causing settlement of the bearing support	S12	0.02
Grates filled with debris causing drainage not function	S13	0.05
Deck inlets not sufficient to carry the runoff causing drainage not function	S14	0.02
Disconnected outlet pipes causing drainage not function	S15	0.02
High traffic volume causing deficiency in joint anchorage	S16	0.03
Heavy traffic volume causing deficiency in joint anchorage	S17	0.07

TABLE 2. Probabilities for Interactions Causing Accelerated Concrete Deck Deterioration

MCS[a] (1)	Intersecting basic events (2)	Probability (3)
S5 ∩ S8	Transverse flexure cracks and damage to joint seals	0.0270
S4 ∩ S8	Flexure cracks and damage to joint seals	0.0250
S5 ∩ S7	Transverse flexure cracks and loose or missing fasteners	0.0189
S5 ∩ S17	Transverse flexure cracks and heavy traffic volume causing deficiency in joint anchorage	0.0189
S4 ∩ S7	Flexure cracks and loose or missing fasteners	0.0175
S4 ∩ S17	Flexure cracks and heavy traffic volume causing deficiency in joint anchorage	0.0175
S1 ∩ S8	Damage to areas exposed to traffic and damage to joint seals	0.0150

[a]Minimum cut set.

interaction of events "damage to bearing and shear areas" and "damage to joint seals" that may interact to contribute to accelerated concrete deck deterioration.

For quantitative analysis of the fault tree the probability of the basic events are needed. Since there are not enough data to establish the probability distribution profile to determine the probability of each basic event, a bridge engineer provided the mean value of probabilities of basic events as shown in Table 1 (Murphy, personal communication, February 1997). In providing the data the engineer assumed that the concrete bridge decks are located at interstate highways and constructed in compliance with standard procedures. In addition the basic event occurrences are assumed independent one from another (mutually exclusive). It should be noted that these assumptions might not be valid in all cases.

After obtaining the basic event probabilities the MCS probabilities can be calculated. Because an MCS is an intersection of two basic events, the probability of the MCS is obtained by multiplying the probabilities of its basic events. For example, using the basic event probabilities in Table 1, the probability of the cut set (S3 ∩ S8) is 0.001.

The relative probability of each MCS establishes its contribution in causing accelerated concrete deck deterioration. In this example the seven most important interactions for causing accelerated concrete deck deterioration are listed in Table 2. The interaction between the basic events "transverse flexure cracks" and "damage to joint seals" has the largest contribution to the occurrence of the top event, with a probability of 0.027. Accordingly, MR&R actions to prevent interaction between "transverse flexure cracks" and "damage to joint seals" may alleviate the occurrence of accelerated concrete deck deterioration.

Finally, the probability of the top event (the accelerated deterioration of concrete deck occurrence due to element interaction) is computed according to (8). The probability of the top event is the union of all the MCSs. If all basic events exist the probability of accelerated concrete deck deterioration is 0.40. If some basic events do not exist then the conditional probability of the corresponding basic events is zero. In this case the probability of accelerated deterioration of the concrete deck due to element interaction can be computed from (8) by substituting the conditional probabilities of zero.

The information about the probability of occurrence of accelerated element deterioration can be used to alert departments of transportation of potential maintenance problems and, subsequently, to direct certain MR&R actions to prevent or mitigate problems. The information can also be used to improve the accuracy of the deterioration rate of the corresponding element by making the necessary adjustment to account for an increase in deterioration rate. However, further study is needed to establish specific procedures for using the MCS probabilities to update deterioration rate.

CONCLUSIONS

Element interaction in bridge deterioration is a phenomenon that leads to acceleration in element deterioration. Element interaction can be critical if it significantly increases deterioration rate of the affected element. Admitting and integrating element interaction phenomena into bridge deterioration models will certainly improve prediction of future bridges' conditions.

The example introduced in the paper is only one of many possible interaction phenomena in bridge deterioration. The sequence of events leading to the top event occurrence in this example may not be exhaustive. These events reflect the nature of interaction and some knowledge acquired from bridge engineers.

This paper introduces an approach to modeling element interaction mechanisms using fault-tree method, one that can be used to identify, represent, and measure interaction phenomena. A fault tree is a qualitative model that can be evaluated

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quantitatively. A fault-tree model is not a deterioration model but can be used in both network-level and project-level models to focus on mitigating accelerated element deterioration by certain MR&R actions, and to improve element deterioration assessments. Systematic implementation of the fault-tree approach must be preceded by field verification.

The fault-tree procedure is well suited, if further developed, for modeling element interaction. However, further investigation is needed before the method can be adopted. Additional investigation is essential to establish and verify a comprehensive quantitative assessment. Currently there is not enough available data to establish a probability distribution profile of basic events to implement the quantitative assessment of the fault-tree method. In addition, more research may be necessary to determine the most efficient way to identify element interactions and to explain the underlying interaction mechanisms. Structure of a fault tree depends on knowledge gained through mechanics-based analysis. Moreover, cost-benefit analysis is required to evaluate the potential payoff of using the fault-tree method to model interaction. Finally, details for integrating the fault-tree results to element-based BMSs systems must be addressed.

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