EVENT TREE ANALYSIS TO PREVENT FAILURES IN TEMPORARY STRUCTURES

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ABSTRACT: In this study, we examined the enabling and triggering events that caused failures in temporary structures. Using event tree analysis, we then analyzed the propagation of component failures. The concept of fuzzy sets is used to manipulate human-based subjective judgments, which are abundant during the construction of temporary structures, and to minimize the complexities of conditional events in the trees. Ranking of critical paths, based on the highest probability of failure, is also presented for quality control purposes.

INTRODUCTION

Many researchers have discussed and evaluated the failures of temporary structures. Feld pioneered the investigations of construction failures caused by inadequacies in the temporary structures (7). Elliott investigated several failure cases of falsework bridges (5). Hadipriono and Wang identified, classified, and documented numerous causes of falsework failures (11).

In this paper, data from the preceding resources and many others (9,10) were used to perform an analysis of failure path/propagation of a substantial failure in temporary structures. For this purpose, the event tree analysis was used as a tool to show sequential component failures. Analyses based on fuzzy set concepts were employed to determine the fuzzy probability of failure of temporary structures. We posit that the method developed herein may be used to reduce failures in the construction of temporary structures.

TEMPORARY STRUCTURE

A temporary structure usually consists of falsework and formwork. A falsework usually supports a main work partially or wholly until it is strong enough to support itself, while a formwork retains plastic concrete in its desired shape until it hardens. A typical bridge falsework and formwork arrangement such as that shown in Fig. 1 was chosen. The temporary structure is composed of four tiers: Tier I, steel tower; Tier II, span support system; Tier III, timber bents; and Tier IV, formwork system.

Tier I is the steel tower shoring that has a capacity of up to 100 kips

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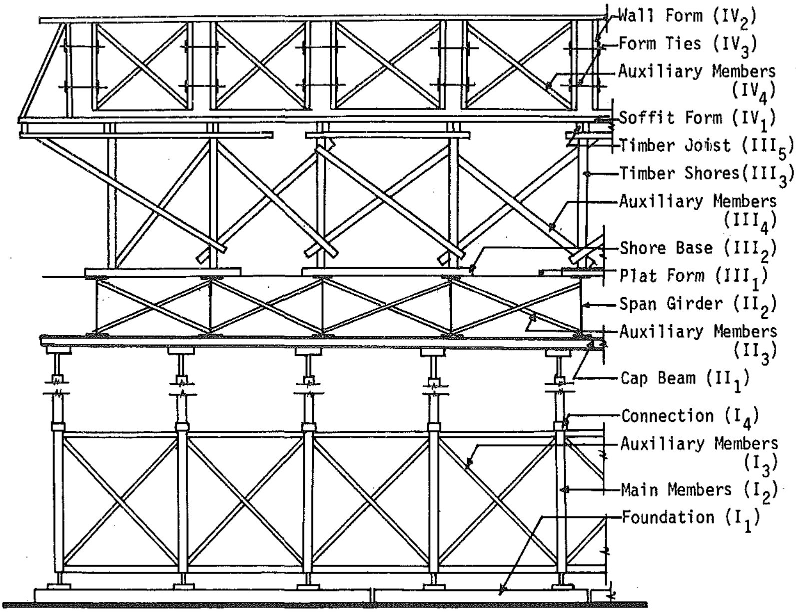

FIG. 1.—Typical Configuration of Temporary Structure

(50 tons) per tower leg. This tier is divided into four major components: foundation, main members, auxiliary members, and connections. The foundation can be made from concrete pad but for a lesser load or stronger ground condition, timber planks can also be used. The main members are the legs that directly support the loads and rest on the foundation. These legs are made from heavy duty steel tubes or structural steel members designed to carry the specified loads. The auxiliary members are the cross bracings and lacings installed to maintain the stability of the main members. For permanent connections, welded joints are used between members, but during falsework installation, members are connected to each other with bolts, pins, or brackets.

Tier II supports the longitudinal span of the bridge. This tier consists of three major components: the cap beams, span girders, and auxiliary members. The steel cap beams are placed on top of the steel towers of Tier I and provide the base for the span girders. These girders, usually made from steel, span between the two towers of Tier I. Auxiliary members are used to brace these girders.

Tier III is usually erected, particularly for a haunched bridge profile, so that the height of these bents can be tailored to maintain the desired elevation of the bridge. This tier consists of five major components: the working platform, shore base, shores, auxiliary members, and joists. The working platform is usually made from timber planks laid on top of the span girders. The shore base is needed to support the shore members; this base is commonly made from timber and wood sills. The shores and auxiliary members are installed to support the joists, which, in turn, support the soffit form of Tier IV.

Tier IV, the top tier, is the formwork that consists of four major components: the soffit forms, wall forms, tie forms, and auxiliary members. The soffit forms are installed immediately on top of the timber joists of Tier III. They are made from plywood strengthened by small joists. The inclined or vertical wall forms are made from plywood stiffened by studs and soldier beams. A pair of wall forms are connected by form ties and braced laterally by the auxiliary members.

The preceding model of the temporary structure may vary with the types of concrete box girder bridges. However, investigations on numerous failure cases revealed only minor variations. Moreover, the analysis of failure mechanisms was performed independently for each tier and, therefore, the analysis can be tailored to accommodate various construction arrangements of the temporary structure. In addition, this model can also be used for other types of structures with minor modifications in the event tree diagrams.

Failure Mechanism

The term "failure" is defined as the incapacity of a structure or its component(s) to perform as specified by the design and construction requirements. Failure could result in "collapse," where all or a substantial part of a structure fails, therefore necessitating full or partial replacement. Both terms are used in this paper to describe the failure mechanisms of each tier. Each of the tiers supporting the permanent structure can fail independently, however, the effects can result in failures of the others. The following describes the failure mechanisms of the structure, with the assumption that failure initiation can occur in any component in any tier:

In Tier I, failure initiation could occur in the foundations, main members, auxiliary members, and connections; however, only failure of the main members is assumed to cause the immediate collapse of the steel tower system. The collapse of the tower will subsequently cause the total collapse of the temporary structure.

Failure in Tier II could initiate at the cap beams, span girders, or auxiliary members; however, only failure of the span girders is assumed to cause the immediate collapse of Tier II. Collapse of this tier will bring down the tiers above it but may or may not cause the failure of Tier I.

Tier III can collapse if the timber shores fail. However, failure can originate at the platform, shore base, timber shores, auxiliary members, or timber joists. The collapse of this tier may or may not result in the collapse of the tiers below it.

The soffit forms, wall forms, ties, or auxiliary members in Tier IV could initiate the collapse of this tier, which subsequently, may or may not result in the collapse of the tiers below it. It is assumed, however, that only the failure of soffit forms or wall forms will cause the immediate collapse of Tier IV.

Failure mechanisms in temporary structures usually occur because of the causes of failures that are described below.

Causes of Failures

A failure usually takes place when both "enabling" and "triggering"

TABLE 1.—Enabling Events

Event number (1)	Tier/component number (2)	Type of enabling event (3)	Performance of components in relation to enabling events[a] (4)
E1	I_1 (Foundations)	Improper treatment of ground conditions (settlement of foundation) —uncompacted subgrades —inadequate soil treatment	VG
E2	I_1 (Foundations)	Improper timber mudsill installation/weak concrete pad —slippage/cracking	F
E3	I_2 (Main members)	Inadequate spacing between members	P
E4	I_2 (Main members)	Use of defective members	VP
E5	I_2 (Main members)	Insufficient load carrying capacity	G
E6	I_3 (Auxiliary members)	Missing/insufficient auxiliary members (bracing or lacing)	F
E7	I_4 (Connections)	Missing/untightened bolts or pins	P
E8	I_4 (Connections)	Poor/deteriorated welded joints	G
E9	II_1 (Cap beams)	Inadequate joints between cap beams	F
E10	II_2 (Span girders)	Insufficient stiffeners to provide stability	P
E11	II_3 (Auxiliary members)	Missing/insufficient auxiliary members (bracing)	VP
E12	II_3 (Auxiliary members)	Inadequately connected auxiliary members to griders	F
E13	III_1 (Platforms)	Loosely laid platforms	VG
E14	III_2 (Shore bases)	Unstable shore bases	G
E15	III_3 (Timber shores)	Inadequate spacing between members	P
E16	III_3 (Timber shores)	Use of defective members	F
E17	III_3 (Timber shores)	Insufficient load carrying capacity —low safety factor	VP
E18	III_4 (Auxiliary members)	Missing/insufficient auxiliary members (bracing or lacing)	P
E19	III_4 (Auxiliary members)	Improperly connected auxiliary members to the shores	VP
E20	III_5 (Timber joists)	Unstable/improperly installed joists	G
E21	IV_1 (Soffit forms)	Disjoint of the soffit forms	F
E22	IV_2 (Wall forms)	Disjoint of wall forms	VG
E23	IV_3 (Form ties)	Insufficient load carrying capacity of snap ties	P
E24	IV_3 (Form ties)	Inadequate spacing of snap ties	F
E25	IV_4 (Auxiliary members)	Insufficient/missing auxiliary members	F
E26	IV_4 (Auxiliary members)	Inadequately connected auxiliary members to wall forms	F

[a]This column should be completed by the assessor.

events occur. An enabling event is one that contributes to a component failure due to design or construction deficiencies. A triggering event is usually an external event, such as construction load or failure of a component that could trigger the failure of another. For example, the "inadequately braced main members of falsework" is an enabling event, while "accidental load from crane operations" is a triggering event.

Data of enabling events were collected and compiled for this research from many sources (1,2,6,8,9,12,13) and are listed in Table 1. These data are related to the components in each tier described earlier. Table 2 shows data collected for the triggering events. The interactions between the enabling and triggering events are shown in Table 3. These interactions were derived from the available data as well as from the writers' experience and judgment. For example, failure of auxiliary members in Tier I can take place due to the occurrence of event E6 (missing/insufficient bracing/lacing) and either one of events T3 (effects from con-

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TABLE 2.—Triggering Events

Event number (1)	Type of triggering events (2)	Magnitude of triggering events[b] (3)
T1	Heavy rain (water flow)/river current causing falsework foundation	VSM
T2	Concentrated/excessive load due to construction material	SM
T3	Effects from concreting operation —vibration, lateral movement	SM
T4	Impact load from concrete pouring debris	MI
T5	Accidental load from construction equipments/vehicles	VSM
T6	Vibration from nearby equipments/vehicles	MI
T7[a]	Effects of improper/premature falsework of formwork removal	SM

[a]Removal of temporary structure (T7) does not interact with any enabling event; however, T7 can be performed on the main members in Tier I and timber shores in Tier III.

[b]This column should be completed by the assessor.

TABLE 3.—Interaction between Enabling and Triggering Events

Enabling events (1)	Triggering Events						
	T1 (2)	T2 (3)	T3 (4)	T4 (5)	T5 (6)	T6 (7)	T7 (8)
E1 (I_1)	X	X	X	X	—	X	—
E2 (I_1)	—	X	X	X	—	—	–
E3 (I_2)	—	X	X	X	—	—	—
E4 (I_2)	—	X	X	X	X	X	—
E5 (I_2)	—	X	X	X	—	—	—
E6 (I_3)	—	—	X	X	X	—	—
E7 (I_4)	—	X	X	X	X	X	—
E8 (I_4)	—	X	X	X	X	X	—
E9 (II_1)	—	X	X	X	—	—	—
E10 (II_2)	—	X	—	X	—	—	—
E11 (II_3)	—	—	X	X	—	—	—
E12 (II_3)	—	—	X	X	—	—	—
E13 (III_1)	—	X	X	X	—	—	—
E14 (III_2)	—	X	X	X	—	—	—
E15 (III_3)	—	X	X	X	—	—	—
E16 (III_3)	—	X	X	X	X	—	—
E17 (III_3)	—	X	X	X	—	—	—
E18 (III_4)	—	—	X	X	X	—	—
E19 (III_4)	—	—	X	X	—	—	—
E20 (III_5)	—	X	X	X	—	—	—
E21 (IV_1)	—	—	X	—	—	—	—
E22 (IV_2)	—	—	X	—	—	—	—
E23 (IV_3)	—	—	X	—	—	—	—
E24 (IV_3)	—	—	X	—	—	—	—
E25 (IV_4)	—	—	X	—	—	—	—
E26 (IV_4)	—	—	X	—	—	—	—

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creting operations), T4 (impact loads from concrete pour/debris), or T5 (accidental loads from construction equipment/vehicles).

Event Tree Analysis

Failure mechanisms of the components in the temporary structure due to the preceding causes of failures are illustrated in event tree diagrams. In this study, seven event trees were developed based on the seven triggering events. Examination of the structure indicates 466 most probable and logical failure paths. One of the trees, having 16 paths is shown in Fig. 2. The event tree, TRIG6, in this figure was constructed based on event T6 that affects the components that experience potential enabling events.

All paths in TRIG6 indicate the sequential failure events of the components. The event initiating the failure at the beginning of a path is related to the occurrence of a triggering event and an enabling event. The event at the end of each path is related to the failure of the component that results in the immediate collapse of the corresponding tier.

For example, in path number 16, i.e., path T6-E8 (I_4)-E6 (I_3)-E5 (I_2), T6 triggers component I_4 whose performance is related to the enabling

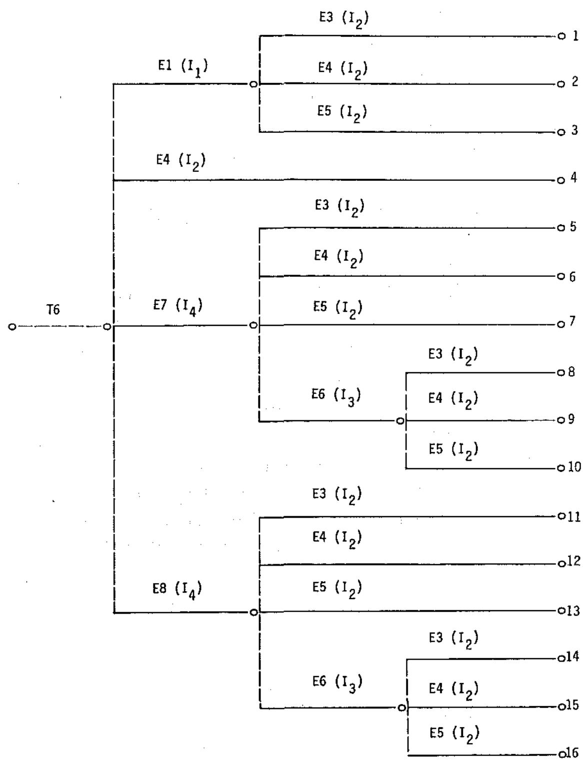

FIG. 2.—Event Tree for TRIG6

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event E8. Subsequently, failure of component I_4 triggers component I_3 that may have experienced the enabling event, E6. Finally, failure of the latter component, coupled with the potential occurrence of E5 in component I_2, causes I_2 to fail, which, in turn, results in the collapse of the total structure.

In this study, we assumed that the triggering event, Ti, takes place at the incipient point of the failure sequence, and therefore, initiates the failure paths in the trees. As can be seen in Table 3, each component in any tier may have experienced more than one enabling event; however, each event was evaluated independently. For example, in Fig. 2, the failure path initiating at the main member of Tier I, component I_2, may experience events E3 (inadequate spacing between members), E4 (use of defective members), or E5 (insufficient load carrying capacity).

The event trees are used as a tool to determine the fuzzy probability of the occurrence of each failure path, and, hence, the criticality of each path which is obtained. We evaluated the probability measure by using the concept of approximate reasoning.

Approximate Reasoning

Several uncertainties, which may be random or human-based, contribute to the component failures of the temporary structure. The concept of reliability, which is based on classical probability theory, emphasizes random uncertainties. The use of this concept requires statistical information about each component. The procedure, however, becomes impractical due to the statistical interdependence that may exist among these components. The knowledge of the performance of a component may be an important factor when assessing the performance of the others. Hence, the use of conditional probabilities pertinent to this analysis could become a major problem.

In addition, the probability-based reliability concept often excludes human-based uncertainties, which abound, particularly in the construction and erection of a temporary structure. Examples of these uncertainties are the enabling and triggering events described earlier. These uncertainties are often evaluates based on one's experience and judgment. They are usually inexact and are commonly expressed in qualitative terms and frequently described using linguistic variables. A linguistic variable is information expressed in words or phrases that has a value which is not clearly defined. For example, the "performance of falsework main members in Tier I" is a linguistic variable whose value can be "good," "poor" or "fair." A "good" performance of falsework main members usually involves the realm of human perceptions, subject to a range of interpretation; therefore, its value, though meaningful, is not clearly defined and may be classified as a fuzzy set.

In this study, we used the concept of fuzzy sets to transform the linguistic values into mathematical representations. Since Zadeh introduced this concept (15), fuzzy set theory has been used in several areas of civil engineering. Blockley assessed structural safety in civil engineering (4), Yao evaluated seismic damage of existing structures (14), and Hadipriono estimated falsework safety (10).

Fuzzy set operations in the following sections are limited to only those pertinent to this study. (The basics of fuzzy set theory can be found in Refs. 3 and 15.) A numerical example is also presented.

Fuzzy Operations

In this study, four linguistic variables were used: (1) Performance (PF) of the components with regards to the enabling events; (2) Magnitude (M) of the triggering events; (3) Consequence (C) of the events on the components; and (4) Probability (PR) of component failure in relation to the consequence. From here on the term "probability" is used to represent the fuzzy probability. Each of these variables has its own linguistic values that can be converted into fuzzy sets, as shown in Table 4. Note that the values assigned in this table are for illustrative purposes only. The membership values are assigned based on subjective judgment. The effect of their variation is discussed in Ref. 10. As an example, a "poor" performance of falsework bracings may be defined by the following:

$$\text{poor} = \left[\frac{1}{0.9}, \frac{2}{0.6}, \frac{3}{0.4}, \frac{4}{0.2}, \frac{5}{0.0}\right] \quad \text{(1)}$$

where "—" is a delimiter. The left and right sides of the delimiters are the elements, x, and the membership values, $f(x)$, of the fuzzy set, respectively. In this example, the elements can be interpreted as the performance level, which may range from "no bracing at all," ($x = 1$), to "rigidly braced falsework," ($x = 5$). Each membership value shows the degree of membership of the corresponding element in the fuzzy set and is a real number in the interval [0,1]. In the above example, the degree

TABLE 4.—Fuzzy Set Value for Linguistic Variables

Performance (1)	Consequence (2)	Magnitude (3)	Probability[a] (4)	Values: $f(x)$ (5)
Very good (VG)	Very severe (VS)	Very large (VLA)	Very low (VLO)	$\left(\frac{x}{10}\right)^6$; $0 \le x \le 10$
Good (G)	Severe (S)	Large (LA)	Low (LO)	$\left(\frac{x}{10}\right)^3$; $0 \le X \le 10$
Fair (F)	Moderate (MO)	Mild (MI)	Medium (ME)	$\begin{cases} \frac{x}{10}; & 0 \le x \le 5 \\ \frac{10-x}{10}; & 5 < x \le 10 \end{cases}$
Poor (P)	Light (L)	Small (SM)	High (H)	$\left(\frac{10-x}{10}\right)^3$; $0 \le x \le 10$
Very poor (VP)	Very light (VL)	Very small (VSM)	Very high (VH)	$\left(\frac{10-x}{10}\right)^6$; $0 \le x \le 10$

[a] $x = 1$ implies the element of fuzzy probability is 10^{-1}, etc.

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of membership is the lowest, 0.0, for 5 and the highest, 0.9, for 1. In other words, the state of the component is close to 1.

It can be seen that the fuzzy set "poor" is contained in the classes of fuzzy sets of the variable Performance. This poor performance can be related to a severe consequence, in which the fuzzy set "severe" is contained in the classes of fuzzy sets of the variable Consequence. This can be done through fuzzy relation: an operation used to relate different fuzzy sets.

Let A and B be two fuzzy sets such that $A \in \phi(X)$ and $B \in \phi(Y)$; $X = \{x1, x2, \ldots, xi, \ldots xm\}$ and $Y = \{y1, y2, \ldots, yj, \ldots yn\}$ are the nonempty sets, and $\phi(X)$ and $\phi(Y)$ denote the classes of all fuzzy sets of X and Y, respectively. The membership function of the fuzzy relation, R from A to B, or $R = A \times B$, is expressed as

$$f_R(xi, yj) = f_{A\times B}(xi, yj) = \Lambda[f_A(xi), f_B(yj)] \quad \ldots\ldots (2)$$

$\forall xi \in X$, $\forall yj \in Y$; for $i = 1$ to m, $j = 1$ to n.

This function can also be represented by the following matrix:

$$f_R(xi, yj) = \mathbf{R}_{\mathbf{A\times B}}\, \boldsymbol{\epsilon\phi}\ (\mathbf{X} \times \mathbf{Y}) = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1j} & \cdots & r_{1n} \\ r_{21} & \cdot & \cdots & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot & \cdots & \cdot \\ r_{i1} & \cdot & \cdots & r_{ij} & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot & \cdots & \cdot \\ r_{m1} & \cdot & \cdots & \cdot & \cdots & r_{mn} \end{bmatrix} \quad \ldots\ldots (3)$$

where r_{ij} is the membership value of each element contained in $\mathbf{R}_{\mathbf{A\times B}}\, \boldsymbol{\epsilon\phi}\ (\mathbf{X} \times \mathbf{Y})$ and is obtained from the minimum/conjunction (Λ) of the membership values $f_A(xi)$ and $f_B(yj)$.

As an example, suppose that the value of "poor" in Eq. 1 is given when assessing the Performance (PF) of a falsework component. Based on this assessment, the Consequence (C) is determined as "severe," given by the following fuzzy set:

$$\text{severe} = \left[\frac{1}{0.9}, \frac{2}{1.0}, \frac{3}{0.6}, \frac{4}{0.3}, \frac{5}{0.0}\right] \quad \ldots\ldots (4)$$

The relation, $\mathbf{R} \in \phi(PF \times C)$, between "poor" and "severe" then yields the following matrix:

R = (PF): .... (5)

		(C): SEVERE				
		1	2	3	4	5
P	1	0.9	0.9	0.6	0.3	0.0
O	2	0.6	0.6	0.6	0.3	0.0
O	3	0.4	0.4	0.4	0.3	0.0
R	4	0.2	0.2	0.2	0.2	0.0
	5	0.0	0.0	0.0	0.0	0.0

Assessment of Fuzzy Probability

The foregoing fuzzy relation was used to determine the values of the

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Probability of a component to fail given the Consequence on the component that results from either the Performance due to the enabling events or the Magnitude due to the triggering events. The event tree models were used to assess the probability values of failure paths.

The Consequence value of each enabling and triggering event was observed and compiled from an earlier study (10) and the writers' own experiences. These values vary with the types of components and events. For example, the consequence on the main member in Tier I due to a certain enabling event may be different from that in the wall form due to another event. The Probability of a component failure was determined subjectively in relation to the Consequence on the component regardless of the types of events. Note that any changes that may be needed for the Consequence and Probability values can be incorporated in the analysis without any difficulties. These values served as a data base to support the analysis of the event trees based on an assessor's subjective assessments. An assessor used Table 1 to estimate the Performance value of each component in relation to the enabling events. Similarly, Table 2 was used to estimate the Magnitude values of the triggering events.

Linguistic values for the foregoing variables were transformed into fuzzy sets as shown in Table 4. These values are based on a modified model of Baldwin's ramp function (3) as shown in Fig. 3. Note that for the Probability values, the fuzzy elements indicate the inverse power (e.g., $x = 1$ implies 10^{-1}, $x = 2$ implies 10^{-2} etc.). The procedures that follow, were then employed to obtain the Probability values for each component in the trees.

Fuzzy relation, **R1**$' \in \phi(\text{PF} \times \text{C})$, exists between the Performance (PF) and Consequence (C) values. It is also observed that fuzzy relation, **R2**$'$ $\in \phi(\text{C} \times \text{PR})$, exists between Consequence (C) and Probability (PR) val-

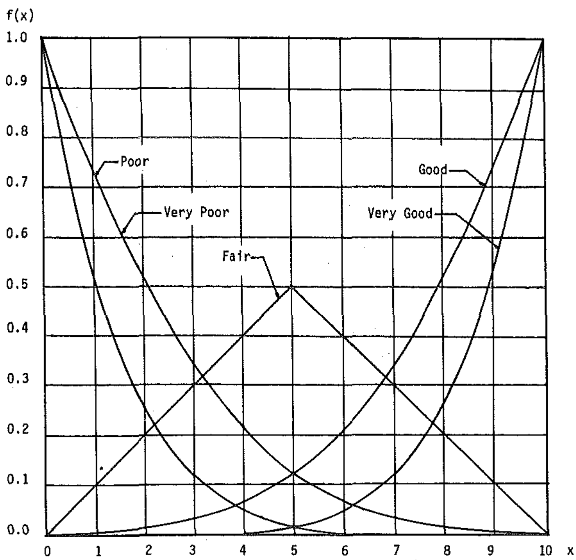

FIG. 3.—Modified Baldwin's Ramp Function

ues. The composition between the two relations produces the fuzzy relation, $\mathbf{R}' \in \phi(PF \times PR)$, which relates the Performance (PF) to the Probability (PR) values. Since the same values for (C) are employed in both $\mathbf{R1}'$ and $\mathbf{R2}'$ the relation $\mathbf{R}'$ can also be found directly from the values of (PF) and (PR). Then, projection on the probability space, i.e., by taking the maximum membership values on this space, results in the fuzzy sets for probability.

Similar manipulation also applies to the triggering events that trigger the first component at the start of the trees. $\mathbf{R1}^* \in \phi(M \times C)$, relates Magnitude (M) to Consequence (C), while $\mathbf{R2}^* \in \phi(C \times PR)$ relates Consequence (C) to Probability (PR). The relation $\mathbf{R}^* \in \phi(M \times PR)$ can be found directly from the values of (M) and (PR). Projection on (PR) yields the required probability.

The final result of the probability value in each failure path is found by taking the conjunction of all fuzzy probability values in the path. The final fuzzy probability value is then converted into a single probability value suggested by Ref. 16. Ranking of important paths can be determined based on these single probability values; those paths with the highest probability will be of primary importance. This procedure is described by the following example.

EXAMPLE

A computer program was developed for the purpose of this example. The input data for the temporary structure are provided by an assessor who is familiar with falsework and formwork erection. The assessor filled Cols. 4 and 3 of Tables 1 and 2, respectively, indicating his/her judgment concerning the components in relation to the performance due to enabling events and to the magnitude of the triggering events.

The event tree TRIG6 in Fig. 2 is used in this example. In order to avoid repetition and since the procedures are the same for all trees, only TRIG6 is discussed and displayed here. As mentioned earlier, TRIG6 consists of 16 paths. The probability of each failure path is found through the following steps:

Step 1.—Compute fuzzy relation, $\mathbf{R}^*(\mathbf{T6}) \in \phi(M \times PR)$, between the magnitude of triggering event, T6, and its corresponding probability through the use of Eqs. 2 and 3. The input data for the magnitude is given by the assessor (see Col. 3 of Table 2). Data for the corresponding probability is provided by the data base created in the computer program, thus, a user does not have to assess the probability value.

Step 2.—Compute fuzzy relations, $\mathbf{R}'(\mathbf{Ei}) \in \phi(PF \times PR)$, between the performance of each component *i* (due to enabling event Ei) and its corresponding probability. The performance values are obtained from the assessor (see Col. 4 Table 1) and the probability values are provided by the data base.

Step 3.—Project all fuzzy relations obtained in steps 1 and 2 on the probability space. This is performed by taking the largest membership value in each column of the fuzzy relation matrix. This step produces fuzzy probabilities for T6 and Ei's.

Step 4.—Perform fuzzy conjunction for all fuzzy probabilities obtained in step 3.

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Step 5.—Compute the expected value of fuzzy elements in step 4 using the following expression (Ref. 16):

$$\mathrm{PR(PATH\ 16)} = \sum_{i=0}^{10} \frac{f(x_i)}{\sum_{j=0}^{10} f(x_j)} (x_i) \quad \cdots\cdots \quad (6)$$

As an example, path number 16 of the tree, TRIG6, indicates a triggering event, T6 (on component I4), and three enabling events, E8, E6, and E5. Step 1 yields the relation, **R*(T6)** $\in \phi(\mathrm{M} \times \mathrm{PR})$ as follows:

		PROBABILITY (PR) 0	1	2	3	4	5	6	7	8	9	10
R* = M	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	1	0.10	0.10	0.10	0.10	0.10	0.10	0.06	0.03	0.01	0.00	0.00
G	2	0.20	0.20	0.20	0.20	0.20	0.13	0.06	0.03	0.01	0.00	0.00
N	3	0.30	0.30	0.30	0.30	0.22	0.13	0.06	0.03	0.01	0.00	0.00
I	4	0.40	0.40	0.40	0.34	0.22	0.13	0.06	0.03	0.01	0.00	0.00
T	5	0.50	0.50	0.50	0.34	0.22	0.13	0.06	0.03	0.01	0.00	0.00
U	6	0.40	0.40	0.40	0.34	0.22	0.13	0.06	0.03	0.01	0.00	0.00
D	7	0.30	0.30	0.30	0.30	0.22	0.13	0.06	0.03	0.01	0.00	0.00
E	8	0.20	0.20	0.20	0.20	0.20	0.13	0.06	0.03	0.01	0.00	0.00
(M)	9	0.10	0.10	0.10	0.10	0.10	0.10	0.06	0.03	0.01	0.00	0.00
	10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(7)

A similar procedure was performed in step 2 to obtain the relation matrices in conjunction with the enabling events E8, E6, and E5 (for brevity, these matrices are not shown here). In step 3, projections on space (PR) of the relation matrices yield the following fuzzy probability:

$$\mathrm{(PR)T6} = \left[\frac{0}{0.50}, \frac{1}{0.50}, \frac{2}{0.50}, \frac{3}{0.34}, \frac{4}{0.22}, \frac{5}{0.13}, \frac{6}{0.06}, \frac{7}{0.03}, \frac{8}{0.01}\right] \quad \cdots\cdots \quad (8a)$$

$$\mathrm{(PR)E8} = \left[\frac{2}{0.01}, \frac{3}{0.03}, \frac{4}{0.06}, \frac{5}{0.13}, \frac{6}{0.22}, \frac{7}{0.34}, \frac{8}{0.51}, \frac{9}{0.73}, \frac{10}{1.00}\right] \quad \cdots\cdots \quad (8b)$$

$$\mathrm{(PR)E6} = \left[\frac{0}{0.50}, \frac{1}{0.50}, \frac{2}{0.50}, \frac{3}{0.34}, \frac{4}{0.22}, \frac{5}{0.13}, \frac{6}{0.06}, \frac{7}{0.03}, \frac{8}{0.01}\right] \quad \cdots\cdots \quad (8c)$$

$$\mathrm{(PR)E5} = \left[\frac{2}{0.01}, \frac{3}{0.03}, \frac{4}{0.06}, \frac{5}{0.13}, \frac{6}{0.22}, \frac{7}{0.34}, \frac{8}{0.51}, \frac{9}{0.73}, \frac{10}{1.00}\right] \quad \cdots\cdots \quad (8d)$$

The conjunction of fuzzy probabilities in Eqs. 8*a*–*d* yields the following (step 4):

$$\mathrm{(PR)T6,\ E8,\ E6,\ E5} = \left[\frac{2}{0.01}, \frac{3}{0.03}, \frac{4}{0.06}, \frac{5}{0.13}, \frac{6}{0.06}, \frac{7}{0.03}, \frac{8}{0.01}\right] \quad \cdots\cdots\cdots \quad (9)$$

In step 5, the expected value of the fuzzy elements in Eq. 9 produces a single probability value of 0.00066. (Note that hand calculation based on the result in Eq. 9 may produce a slightly different answer due to round-off error.)

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TABLE 5.—Ranked Critical Paths and Their Probability for TRIG6

Path number (1)	Probability (2)	Critical (3)
1	0.38200	Yes
2	0.38200	Yes
15	0.38200	Yes
14	0.38200	Yes
5	0.38200	Yes
12	0.38200	Yes
11	0.38200	Yes
6	0.38200	Yes
9	0.38200	Yes
8	0.38200	Yes
4	0.00494	
7	0.00066	
10	0.00066	
13	0.00066	
3	0.00066	
16	0.00066	

Finally, the rank of each path is determined based on the final probability values. The ranked paths are listed in Table 5; those with the highest probability are placed on top. Suppose that a probability limit is determined as 0.005, this limit will put all the paths beyond it on a critical list. Note that this probability limit is taken from the expected value of the fuzzy probability value of "medium." Based on this critical list, an assessor may go through each path and recommend suggestions for improving construction practices.

Conclusions

A simple procedure for assessing the fuzzy probability of failure of temporary structures was developed to determine the most probable paths of progressive failures. Knowledge of these failure paths will serve several purposes. First, it will enable a construction engineer to predict potential collapses in temporary structures. Since the potential enabling and triggering events in the critical paths are readily seen, a quality control process can be established. In addition, the components that lie on these paths can be improved by minimizing the potential enabling and triggering events. As a result, the fuzzy probability of failure through these paths will be reduced.

Although the model in this study represents a particular temporary structure, the procedure can also be applied to various configurations of falsework and formwork with minor modifications.

Appendix I.—References

1. Allen, D. E., "Errors In Concrete Structures," Structures Section, Division of Building Research, National Research Council of Canada, Ottawa, Ontario, Canada, 1979, pp. 465–466.

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2. "AEPIC's Reason for Being," ENR Editorials, *Engineering News Record*, July 7, 1983, p. 64.
3. Blockley, D. I., "The Nature of Structural Design and Safety," John Wiley and Sons, New York, N.Y., 1980.
4. Blockley, D. I., "The Role of Fuzzy Sets in Civil Engineering," *Fuzzy Sets and Systems*, Vol. 2, 1979, pp. 267–278.
5. Elliott, A. L., "Falsework Failures: Can They Be Prevented?" *Civil Engineering*, ASCE, Oct., 1973, pp. 74–76.
6. *Engineering News Record*, McGraw-Hill, New York, N.Y., 1960–1983.
7. Feld, J., "Construction Failure," John Wiley and Sons, Inc., New York, N.Y., 1968, pp. 353–368.
8. Fraczec, J., "ACI Survey of Concrete Structure Errors," *Concrete International*, Dec., 1979, pp. 14–20.
9. Hadipriono, F. C., "Analysis of Events in Recent Structural Failures," *Journal of Structural Engineering*, ASCE, Vol. 111, No. 7, July, 1985, pp. 1468–1481.
10. Hadipriono, F. C., "Assessment of Falsework Performance Using Fuzzy set Concepts," *Structural Safety*, No. 3, Oct., 1985, pp. 47–57.
11. Hadipriono, F. C., and Wang, H. K., "Analysis of Causes of Falsework Failures in Concrete Structures," *Journal of Construction Engineering*, ASCE, Vol. 112, No. 1, Mar., 1986, pp. 112–121.
12. *New Civil Engineer*, The Institution of Civil Engineers, United Kingdom, 1977–1983.
13. *New Civil Engineer International*, The Institutional of Civil Engineers, United Kingdom, 1978–1983.
14. Yao, J. T. P., "Damage Assessment of Existing Structures," *Journal of the Engineering Mechanics Division*, ASCE, Vol. 106, No. EM4, Proc. Paper 15653, Aug., 1980, pp. 785–799.
15. Zadeh, L. A., "Fuzzy Sets," *Information and Control*, Vol. 8, 1965, pp. 338–353.
16. Zadeh, L. A., "Probability Measures of Fuzzy Events," *Journal of Mathematical Analysis and Applications*, Vol. 23, 1968, pp. 421–427.

Appendix II.—Notation

The following symbols are used in this paper:

$A \times B$ = relation from set A to B;
C = Consequence;
$f_A(x)$ = membership function of x in A;
M = Magnitude;
PF = Performance;
PR = Probability;
X = nonempty set;
$x \in A$ = x contained in fuzzy set A;
$\forall x$ = for all values of x;
$\phi(X)$ = classes of all fuzzy set of X;
$\wedge$ = conjunction (minimum); and
$\vee$ = disjunction (maximum).