Deductive Tree Analysis for Evaluating the Reliability of Construction Operations

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INTRODUCTION

The importance of structural and construction safety is associated with the adverse consequences that may result from a structural failure and a construction accident. One of the most important objectives of any construction team is to minimize and control the risk levels of failure and accident of construction operations, as well as to determine the various critical factors which might lead to the increase of the probability of failure and accident of the operations.

There are several uncertainty events and factors that contribute to the failure and accident of construction operations. The factors are associated with random, human-based or system uncertainty. Some of these factors include the level of engineering knowledge and experience, level of workmanship and attitude, level of communication procedures, methods and sequence of construction. Most of these factors are subjective, vague, and imprecisely defined, and therefore, they are expressed in semantic terms rather than mathematical measures. The subjectivity of the factors needs to be incorporated into the reliability estimation process.

The objective of this paper is to present a reliability evaluation methodology for construction operations that considers the effect of the factors and their uncertainties on the estimation of the risk measures for construction operations. The methodology is based on a deductive tree analysis approach which involves identifying a possible condition of the construction system and determining the various events and combination of the factors that contribute to the occurrence of that condition.

The typical deductive tree approach which is used in this paper, involves the Fault Tree Analysis (FTA). In FTA, the possible conditions of the overall system of construction operations is called the undesired event. Therefore, for the purpose of this study the undesired event is defined as the failure and/or accident of construction operations. The FTA is a valuable tool for analyzing and evaluating the safety and reliability of construction operation systems.

DESCRIPTION OF THE METHODOLOGY

The methodology for evaluating the reliability of construction operations is divided into two major components. The first component involves the identification of the types of uncertainty, events and factors that contribute to the failure and/or accident of the construction operations. In addition, it involves the development of the fault tree logical representation for the construction operations system including various sequential and parallel combinations of possible events and factors in a predefined system that may lead to the occurrence of the undesired event. The second component consists of the assessment of the factors and the evaluation of various events and uncertainties involved in the fault tree system of the construction operations. A detail discussion of the various components of the deductive tree analysis for evaluating the reliability of the construction operations is presented in the subsequent sections.

Development of the Fault Tree

The development of the fault tree logical diagram for the construction operations' system depends on four important stages which include: (1) identification of the type of uncertainty involved in the operation, (2) definition of the events that contribute to the failure and accident of the operation, (3) definition of the factors that affect the safety and reliability of the construction operation, and (4) definition of various parallel and sequential combinations of all major possible events affecting the operation.

There are many uncertainties which affect the safety of construction operations. Such uncertainties are usually expected during the progress of construction operations. The different types of uncertainty include random, system, and human-based (Blockley, 1980; Nowak 1980; Yao & Furuta, 1986). The random type of uncertainty involves construction events which are either certain or probable to occur, as well as the events that are precisely defined and described. The random uncertainty is caused by either natural events, such as wind, earthquakes, or by man-made hazards, such as fire, collision, and explosion. On the other hand, system and human-based types of uncertainty involve vagueness, and lack of precision in defining and describing structural and construction events. Human-based uncertainty is a major factor in construction failures and accidents. It is defined as the departure from common engineering practices (Nowak & Carr, 1985).

There are three types of event symbols in the fault tree diagram. They include factors related to the basic events, factors related to the progressive events, and intermediate events.

The factors related to basic events, are usually represented by a circle. Such factors are considered to be critical elements of the fault tree logic system and require further development since they can activate independently to cause failure and accident.

The factors related to progressive events, are represented by a diamond. Such factors need to act together to cause failure and accident of construction operations. Therefore, the progressive events can initiate the failure and accident of construction operations only if the occurrence of the factors relative to two different types of uncertainty in a certain level act together. In addition, it is important to mention that the factors relative to progressive events require no further development.

The intermediate event, is a fault event which indicates an output state for a logic gate of the fault tree. This event requires further development and it is often represented by a rectangle. This event may be well designed to define the different modes and deficiencies relative to the basic and progressive events that contribute to the undesired top event.

Finally, the fault tree diagram is developed before the start of the construction work, but it usually represents to the best knowledge of the expert the construction system during actual construction stage. Therefore, the fault tree logic sequences may be updated, since changes in planning, design, and construction procedures may develop along the work performance of the project.

Evaluation of the Fault Tree

The methodology for safety evaluation of construction operations is based on determining certain variables for each factor that affect the safety of construction operations and then quantitative evaluation of the logic sequences and combinations of the factors in the fault tree diagram, can predict the level of reliability of the construction operations system.

The variables which determine the level of risk associated with the safety performance of construction operation are the state of the factors, S, the frequency of occurrence of the factor, F, and the sensitivity level of the safety of construction operations to each factor's state and frequency (Eldukair & Ayyub, 1988a).

The sensitivity level of the reliability of the operations to the state of the factor can be measured by the degree of having adverse consequences, C, on the performance of the operation. In addition, the sensitivity level of the safety of the operation to the frequency of the factor can be measured by its effect on the risk of failure and accident, R, of the construction operations.

The variables affecting the reliability of the construction operations system are often expressed based on experts' judgment, qualitatively, i.e., semantic terms, rather than quantitatively, i.e., mathematical measures. The concept of the theory of fuzzy sets and systems is used to assess and evaluate the semantic terms into mathematical measures. The assessment of the qualitative description of the variables depends on the selection of fuzzy models for membership functions. Several models exist and their use depends on the experts' judgment.

The estimation of the risk level of failure and accident of the construction operations is determined based on certain fuzzy relationships which incorporate the uncertainty involved in the factor's variables as well as demonstrate the effect of the state of the factors and frequency of occurrence on the safety of the operation.

The effect of the state of each factor on the safety of the construction operation can be developed by combining the state S_i, and the adverse consequences C_j measures for each factor, by a fuzzy cartesian product relation. The membership function of such relation is defined as:

$$\mu_{S \times C}(s_i, c_j) = \min [\mu_S(s_i), \mu_C(c_j)] \quad \text{.......... (1)}$$

where $\mu_{S \times C}(s_i, c_j)$ is the membership of the ordered pairs (s_i, c_j) and $\mu_S(s_i)$ and $\mu_C(c_j)$ are the membership values of the state and consequences variables, respectively.

Then the total effect of all the factors' state E, on the reliability of the operation can be determined by taking the fuzzy union of all the cartesian relations. The membership function of the total effect of the factors' state, E, can be developed as:

$$E = \overset{n}{U} [\mu_{S \times C}(s_i, c_j)] \quad \text{.......... (2)}$$

where $\overset{n}{U}$ is the fuzzy union relation of n sets of cartesian relations between the state and the consequences of the factors.

Similarly, the effect of the frequency of occurrence of each factor on the reliability of the operation can be developed by combining the frequency of the factor F_j, and the risk of failure and accident of the operation R_k, for each factor, by a fuzzy cartesian relationship. The total effect of the frequency

T, on the risk level can be evaluated by the fuzzy disjunction, i.e., union relationship.

A standard fuzzy relation K, between the adverse consequences and the risk of failure and accident of the operation need to be developed. Such relation is usually developed based on experts judgment in relation to the safety performance of the construction operation. In order to achieve an estimate of the risk of failure and accident of the operation due to the effect of the state of the factors, a fuzzy composition relation M, between fuzzy relations E and K needs to be developed. The membership function of such relation is defined as:

$$M = \mu_{E \circ K}(s_i, r_k) = \max_{c_j} \{ \min [\mu_E(s_i, c_j), \mu_K(c_j, r_k)] \} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where $\mu_{E \circ K}(s_i, r_k)$ is the membership value of the fuzzy composition relation between the total effect of the state of the factors and the standard consequences and risk measures, $\mu_E(s_i, c_j)$ is the membership value of the total effect of the state of the factors, and $\mu_K(c_j, r_k)$ is the standard relation of the ordered pairs of the consequences and risk measures.

The final stage for the assessment of the factors involve the determination of a subjective estimate of the risk of failure and accident of the operation. This can be achieved by considering the joint intensity of the state and the frequency of the factors on the risk measure of the operation (Eldukair & Ayyub 1988a,b; Eldukair & Ayyub, 1989). It is important to indicate that this joint relation consists of three fuzzy surfaces. The first surface represents a matrix of membership function for all ordered pairs of the state of the factors and risk measures. The second surface represents a matrix of membership function for all ordered pairs of the frequency of occurrence of the factors and risk measures, and the last surface represents a number of matrices of membership functions for the elements of the fuzzy risk measure. The fuzzy membership function of the final surface is defined as:

$$\mu_{M,T}(s_i, f_j)(r_k) = \min_{s_i} [\mu_M(s_i, r_k), \mu_T(f_j, r_k)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where $\mu_{M,T}(s_i, f_j)(r_k)$ is the joint membership function of the state and frequency of occurrence of the factors, $\mu_M(s_i, r_k)$ is the membership value of the effect of the state of the factors on the risk measures of the operation, and $\mu_T(f_j, r_k)$ is the membership function of the effect of the frequency of occurrence of the factors on the risk measures of the operation.

The next step after completing the assessment of the factors and determining risk measures along all the logic sequences and combinations of the factors, a fuzzy fault tree evaluation is needed across the different modes of failure of the operation system to determine a subjective estimate of the actual risk of failure and accident of the undesired top event. In order to determine such subjective estimate, the following steps should be considered:

1. The probability of failure and accident of the operation due to the occurrence of the different basic and progressive events should be evaluated in fuzzy set measures so that to keep the fuzziness resulted from the uncertainty assessment involved in the problem to the top event of the fault tree.

2. The logic gate relations between the various intermediate events and the undesired top event of the fault tree which have been decided on by the experts judgment need to be evaluated. The membership function of the fuzzy probability of the occurrence of the output event, of AND and OR gates of the fault tree, respectively, can be calculated as proposed by the authors by the following two equations.

AND gate : $P_{fo} = [(x,y) \mid \min\{\mu(x), \mu(y)\}]$ .... (5)

where P_{fo} is the probability of the output of the fault event, (x,y) is the ordered pair of the risk value, $\mu(x)$ and $\mu(y)$ are the membership values of the independent input factors for x and y elements, respectively.

OR gate : $P_{foo} = [(x,y) \mid \max\{\mu(x), \mu(y)\}]$ .... (6)

where P_{foo} is the probability of the output of the fault event, (x,y) is the ordered pair of the risk value, $\mu(x)$ and $\mu(y)$ are the membership values of the independent input factors for x and y elements, respectively.

Applying these two steps along the various modes of failure of the fault tree, a subjective measure of the risk level of the undesired or the top event, i.e., probability of failure of the system, can be determined. Such subjective measure is determined based on a fuzzy membership function which expresses the degree of believe of the risk elements. Therefore, based on this fuzzy membership function, the engineering expert can determine and predicate the range for the level of risk for performing the construction operation. On the other hand, in order to determine a crisp value for the level of risk of the construction operation, an expected value of the power order of the risk measure needs to be developed. The method suggested by Ayyub and Haldar (1985) to calculate the expected value of the power order of the element is more appropriate when dealing with smaller or larger values than the normal [0-1]. Thus, the expected fuzzy probability of fuzzy event A, $E_p(A)$, can be evaluated for a discrete case as:

$$E_p(A) = \sum_{i=0}^{n} \frac{\mu_A(x_i)}{\sum_{i=0}^{n} \mu_A(x_i)} \cdot (x_i) \quad \text{.................................... (7)}$$

where $\mu_A(x_i)$ is the membership function for fuzzy subset A, whose power order elements are x_i.

SUMMARY AND CONCLUSIONS

In general, the estimate of the risk level of structural and construction systems is dependent on the conditions of the factors affecting the system, as well as the various events associated with such factors. In addition, the logic sequences and combinations of the factors are also important elements for evaluating the fault of the system.

The reliability evaluation methodology based on a deductive approach is a valuable tool since it appraises more consistent estimates of the risk measures of construction operations. It can be used as a control tool for engineering practitioners to assess the factors affecting the safety of construction operations at any time along the construction phase of the building process. On the other hand, the evaluation methodology also can be used to modify construction strategies when certain faults occur, and predict critical factors and uncertainty events that contribute to the failure and accident of the construction operations.

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