Reliability-based Failure Cause Assessment of Collapsed Bridge during Construction

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ABSTRACT

There are many uncertainties in structural failures or structures, so probabilistic failure cause assessment should be performed in order to consider the uncertainties. However, in many cases of forensic engineering, the failure cause assessments are performed by deterministic approach though number of uncertainties are existed in the failures or structures. Thus, deterministic approach may have possibility for leading to unreasonable and unrealistic failure cause assessment due to ignorance of the uncertainties. Therefore, probabilistic approach is needed to complement the shortcoming of deterministic approach and to perform the more reasonable and realistic failure cause assessment.

In this study, reliability-based failure cause assessment (reliability based forensic engineering) is performed, which can incorporate uncertainties in failures and structures. For more practical application, the modified ETA technique is proposed, which automatically generates the defected structural model, performs structural analysis and reliability analysis, and calculates the failure probabilities of the failure events and the occurrence probabilities of the failure scenarios. Also, for more precise reliability analysis, uncertainties are estimated more reasonably by using bayesian approach based on the experimental laboratory testing data in forensic report.

1. Introduction

Until recently, there have been several failures of bridge in Korea, such as collapses of Hang-ju Grand Bridge and Sung-su Grand Bridge, etc.. Failures of critical bridge may cause numerous economic and human losses as well as indirect losses. Therefore, failure cause assessment should be performed very significantly to avoid the repetition of earlier bridge failures.

For the reliability-based failure cause assessment, an event tree analysis (ETA) is used in this study, and the event tree is constructed based on the failure events observed in field by forensic investigators. Each sequence of failure events of event tree represents a failure scenario. Among these failure scenarios, the failure scenario representing the highest occurrence probability will be the most critical failure scenario, and the initial failure event of the most critical failure scenario will be defined as the failure cause which triggered the bridge collapse.

To estimate the occurrence probability of each failure scenario, the conditional failure probability including the prior failure events should be calculated for each failure state. And the conditional failure probability can be evaluated by reliability analysis using structural analysis for defected structure by prior failure events.

For more practical application, a modified ETA technique is proposed, which automatically generates the defected structural model, performs structural analysis and reliability analysis, and calculates the failure probabilities of the failure events and the occurrence probabilities of the failure scenarios. Also, for more precise reliability analysis, uncertainties are estimated more reasonably by using the Bayesian approach based on the experimental laboratory testing data in the forensic report.

To achieve the reliability-based failure-cause assessment and compare with deterministic approach, and discuss the applicability of the proposed technique, it is applied to the Hang-ju Grand Bridge which has been collapsed during construction.

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2. Reliability-based forensic engineering model

Due to rapid development in the probabilistic approach to the assessment of the structural failures, the reliability-based model and methods are becoming a powerful tool for analysis and assessment of forensic engineering in practice. Therefore, in this study, a cause assessment model for the reliability-based forensic engineering is proposed, which can give more reasonable results by considering the uncertainties involved in the failure of a structure, as shown in figure 1.

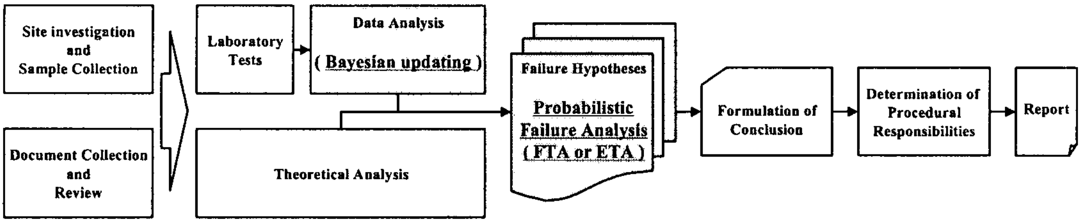


Figure 1 Model of reliability-based forensic engineering

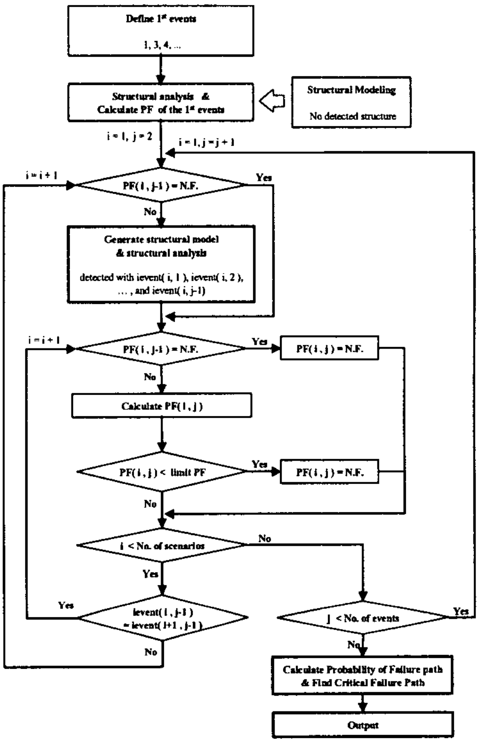
3. Modified ETA technique

The most common mistake made by novice and experienced investigators is failure to consider all possible failure hypotheses. Then, investigators sometimes may mistake to omit the significant and critical failure hypotheses. Therefore, modified ETA technique is proposed in this study which can find the critical failure scenario with considering all of the possible failure hypotheses and perform efficiently without spending much cost and time.

In modified ETA technique, the occurrence probabilities are calculated for all possible combinations of failure events confirmed in the field investigation. In order to evaluate occurrence probability of each failure scenario, quantitative analysis (Evaluation of the conditional probability) of the failure event is performed. If the conditional probability of the failure event is less than the lower limit of the failure probability (For example, $P_f = 0.0003167$ corresponding to the reliability index $\beta = 4.0$), it is regarded that the failure scenario including this failure event will not occur (No Failure).

As a result, several failure scenarios will be remained and the most possible failure scenario will be defined as the most critical failure scenario.

The above may be formalized to the following algorithm. And, figure 2 shows the flow of modified ETA technique.



ievent(i , j) = Event No. of j-th path in i-th scenario

PF(i , j) = Conditional failure probability of j-th path in i-th scenario

Figure 2 Flow of modified ETA technique

step 1. Identification of the failure events.
:Events are confirmed in the field investigation.
step 2. Identification of the initiating failure events.
:All failure events may probably be the initiating failure events.
step 3. Structural analysis for the structural model before collapse.
step 4. Probabilistic analysis for initiating failure events.
:Estimate the failure probability.
step 5. Structural analysis for the structural model including the prior failure events

step 6. Conditional probabilistic analysis for failure events.
step 7. Iteration of the step 5 and step 6
:The failure scenarios were not defined as N.F. until end of all failure scenarios.
step 8. Estimate the occurrence probabilities of each survived failure scenarios.
:$P(path_i) = P(E_{1st}) \cdot P(E_{2nd}) \cdot P(E_{3rd}) \cdot P(E_{4th})$
step 9. Find the most critical failure scenario and cause.

4. Application

4.1 General description of the Hang-Ju Grand Bridge

At approximately 18:30 p.m. on 31 July 1992, the Hang-ju Grand Bridge across Han-river in Seoul, Korea, which is a cable stayed bridge, collapsed immediately during construction. The Hang-Ju Grand Bridge has been designed with 1,460m of total length and 14.5m of width. The bridge also has designed as two types of bridge as follows :

1) Concrete cable stayed bridge - 3-main spans (total length, 320m) at center of bridge
2) PSC (Pre-Stressed Concrete) box girder bridge - the other spans (total length, 1,140m)

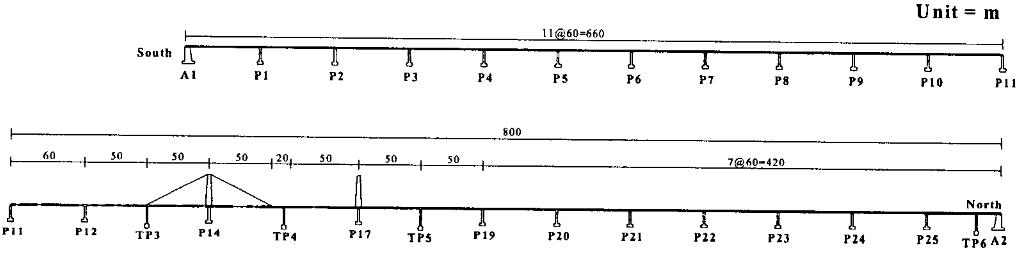


Figure 3 Hang-Ju Grand Bridge

Before the collapse, substructure had been constructed, and PSC box girders had been constructed as continuous-beam type by ILM (Incremental Launch Method). However, the cable had just been installed only at one tower without pre-stressing force as shown in figure 3.
In forensic report, only these two scenarios were considered as the major failure scenario in forensic report among many other possible scenarios, but it was not showed clearly what scenario bridge collapse followed.

4.2 Failure Events

It is certain that the failure path of the collapsed bridge was sequence of the failure events appeared in the collapse. Therefore, if it could be assumed that all of the failure events had been identified by forensic investigators, only the failure events confirmed in the field investigation must be considered to find the critical failure scenario for collapsed bridge. In this study, it is assumed that all of the failure events were identified by forensic investigators, then failure cause assessment is performed with identified failure events in the forensic report. It is need to define the notations representing failure events to perform the event tree analysis by using proposed modified ETA technique. Based on the forensic report, the failure events included in the bridge collapse are described as follows :

1) Rupture of Cable : Defined as E_1
2) Collapse of tower due to bending moment : Defined as E_2
3) Fracture of girder due to negative bending moment at P14 : Defined as E_3
4) Shear slip or bending fracture of the construction joint of girder far from TP4 in southern direction about 5m : Defined as E_4
5) Collapse of TP4 : Defined as E_5
6) Fracture of girder due to positive bending moment far from TP4 in northern direction about 11m : Defined as E_6
7) Fracture of girder due to negative bending moment at P17 : Defined as E_7

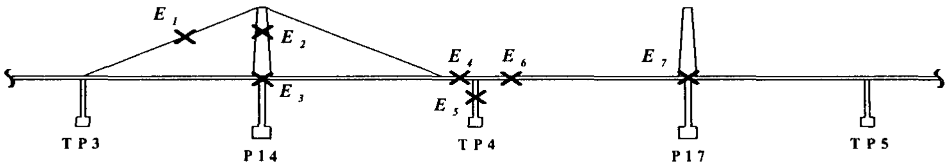


Figure 4 Locations of the major failure events

4.3 Limit state function

In this section, the limit states to perform the reliability analyses are composed of all the possible failure events considered in the forensic report as shown in Table 1.

Table 1 Limit State Functions

Failure Events	Limit State Function	
E_1 : Rupture of Cable	$g(\cdot) = T_R - T_S = A_s \times f_u - T_S$	
E_2 : Collapse of tower due to bending moment	$g(\cdot) = M_R - M_S$	
E_3 : Fracture of girder due to negative bending moment at P14	$g(\cdot) = M_R^- - M_S^-$	
E_4 : Shear slip or bending fracture of the construction joint	Shear Slip	$g(\cdot) = \mu_j(A_s \cdot f_y + N_w) - S_w$
	Bending Fracture	$g(\cdot) = M_R - M_S$
E_5 : Collapse of TP4	$g(\cdot) = M_R - (\mu \times P + H_{impact}) \times L$	
E_6 : Fracture of girder due to positive bending moment far from TP4 in northern direction about 11m	$g(\cdot) = M_R - M_S$	
E_7 : Fracture of girder due to negative bending moment at P17	$g(\cdot) = M_R^- - M_S^-$	

where T_R is the resistance of cable; T_S is the applied tensile force; A_s is the area of the reinforcing steels; f_u is the ultimate tensile strength of reinforcing steel; M_R is the resistant moment of tower ; M_S is the applied bending moment; M_R^- is the resistant negative bending moment of girder at P14; M_S^- is the negative bending moment applied in the girder at P14; S_w is the shear force affecting the web; S is the shear force affecting the whole section; $H(=\mu \times P)$ is transverse load; and μ is coefficient of friction.

4.4 Uncertainties & Bayesian updating

The evaluation of reliability requires information on uncertainty, as presented by the standard deviation or covariance of variation (C.O.V.). The determination of these uncertainties constitutes an essential task in the evaluation of engineering reliability.

In this study, most of the uncertainties of the basic random variables of resistance and load effects are obtained from data available in Korea. Whereas, if the data are not available, those uncertainties are estimated based on bayesian updating.

For the precise comparison of the failure scenarios, it is noted that reliability analysis is performed reasonably. Moreover, for the reasonable reliability analysis, probabilistic distribution parameter is also reasonably estimated. These parameters can be determined from laboratory test data or simulation. However, parameter values obtained from experiments may have uncertainties. Therefore, bayesian updating is used as a balanced estimation technique which incorporated systematically with observed data.

The probabilistic distribution parameters and statistical uncertainties treated as random variables included in reliability analysis are summarized in table 2.

4.5 Critical Failure Scenarios by Modified ETA technique

In this study, there are major 7 failure events included in the bridge collapse, the number of the possible combinations of failure events is 5040 (=7!). By using modified ETA technique, 155 available failure scenarios were found by ignoring the unreasonable failure scenarios of which failure events have the poor conditional failure probabilities $(P(E_i) < P_{limit})$. Therefore, it may be stated that the modified ETA technique is very efficient to find possible critical failure scenarios considering all possible failure scenarios. Table 3 shows critical failure scenarios and their occurrence probabilities, and table 4 shows the conditional probabilities of the failure events.

Table 2 Random variables and probabilistic distribution parameter

	Random variables		Bias	C.O.V.	Ref.
Cable	Area of reinforcing steel,	A_s	1.000	0.015	Nowak et. al. [1994]
	Ultimate strength of reinforcing steel,	f_u	1.097 (1.060)	0.042 (0.070)	Ayyub [1998]
	Tensile force by supplied load,	T_S	1.050	0.100	Nowak [1999]
Girder	Area of tendon,	A_p	1.000	0.015	Nowak et. al. [1994]
	Area of reinforcing steel,	A_s	1.000	0.015	Nowak et. al. [1994]
	Pre-stressing stress,	f_{ps}	1.000	0.040	Al-Harthy-Frangopol [1997]
	28-day yield strength of concrete,	f_{ck}	0.928 (0.920)	0.119 (0.180)	Nowak et. al. [1994]
	Yield strength of reinforcing steel,	f_y	1.033 (1.120)	0.058 (1.033)	Nowak [1995]
	Modulus of Elasticity, steel	E_s	1.000	0.060	Tabsh-Nowak [1991]
	Modulus of Elasticity, tendon(steel),	E_p	1.000	0.060	Tabsh-Nowak [1991]
	Axial force by supplied load,	N	1.050	0.100	Nowak [1999]
	Bending moment by supplied load	M_S	1.050	0.100	Nowak [1999]
	Shear force by supplied load,	S_S	1.050	0.100	Nowak [1999]
Pire	Area of tendon,	A_p	1.000	0.015	Nowak et. al. [1994]
	Pre-stressing stress,	f_{ps}	1.000	0.040	Al-Harthy-Frangopol [1997]
	28-day yield strength of concrete,	f_{ck}	0.997 (0.920)	0.098 (0.180)	Nowak et. al. [1994]
	Modulus of Elasticity, tendon(steel),	E_p	1.000	0.060	Nowak [1999]
	Axial force of TP4,	P	1.050	0.100	Nowak [1999]
Tower	Moment resistance,	M_R	1.120	0.135	Nowak [1999]
	Bending moment by supplied load,	M_S	1.050	0.100	Nowak [1999]

*( ) : Bias & C.O.V. before updating

From the result, it is possible to compare the possibility of critical failure scenarios and failure events quantitatively based on the occurrence probabilities and conditional failure probabilities.

As shown in table 3 and table 4, all of 155 failure scenarios begin with collapse of TP4 (E_5) or shear slip of the construction joint (E_4) which are equal to the intial events in forensic report, and the collapse of TP4 ($P(E_5)=0.13710$) is more possible than the shear slip at the construction joint ($P(E_4)=0.06291$). Also, there are two most critical failure scenarios representing the highest occurrence probability ($P_{occurrence}=0.137$).

Table 3 Failure scenarios

No.	Failure scenarios							P_{occur} of scenario
	1st	2nd	3rd	4th	5th	6th	7th	
1	5	1	2	6	3	4	7	0.137000
2	5	1	6	2	3	4	7	0.137000
3	5	1	2	4	3	7	6	0.137000
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
155	5	4	7	6	2	1	3	0.000002

Table 4 Conditional failure probabilities

No.	Conditional failure probabilities							P_{occur} of scenario
	1st	2nd	3rd	4th	5th	6th	7th	
1	0.137100	1.000000	1.000000	1.000000	1.000000	0.999600	1.000000	0.137000
2	0.137100	1.000000	1.000000	1.000000	1.000000	0.999600	1.000000	0.137000
3	0.137100	1.000000	1.000000	1.000000	1.000000	1.000000	0.999200	0.137000
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
155	0.137100	0.000519	1.000000	0.999200	0.030130	1.000000	1.000000	0.000002

Above two failure scenarios(No 1 & 2) are appeared by using modified ETA technique, which are not considered in forensic report. Therefore, modified ETA technique guarantees to avoid effectively mistaking to omit a significant failure hypotheses.

The most critical failure scenario (with engineering judgement)
1) E_5 : Collapse of TP4
2) E_1 : Severance of Cable
3) E_2 : Collapse of tower due to bending moment
4) E_4 : Shear slip of the construction joint of girder far from TP4 in southern direction about 5m
5) E_3 : Fracture of girder due to negative bending moment at P14
6) E_7 : Fracture of girder due to negative bending moment at P17
7) E_8 : Fracture of girder due to positive bending moment far from TP4 in northern direction about 11m

5. Concluding Remarks

Based on the results from the application to the Hang-ju Grand Bridge, the main observations and findings of this study can be summarized as follows :

1) The most critical failure scenario and cause were found effectively by probabilistic approach proposed in this study. And time and cost to evaluate the occurrence probabilities of all failure scenarios were saved by using modified ETA technique
2) The modified ETA algorithm guarantees to avoid effectively mistaking to omit a significant failure hypotheses, and is very efficient to find possible critical failure scenarios considering all possible failure scenarios, which found 155 available failure scenarios from 5040 failure scenarios.
3) The reliability-based failure cause assessment proposed in this study can evaluate the rank of failure scenario in spite that deterministic approach in forensic report couldn't. Thus, the critical failure scenarios and cause could be found reasonably.
4) It is concluded that the Hang-ju Grand Bridge was collapsed in the second failure scenario in forensic report according to the result of reliability-based failure cause assessment and the engineering judgement in forensic report. And the collapse of TP4 triggered the bridge collapse.

References

1. Al-Harthy, A.S. and Frangopol, D.M. (1997), Integrating System Reliability and Optimization in Prestressed Concrete Design, Computers & Structures, Vol. 64, No. 1-4, pp.729~735.
2. Andrzej s. Nowak (1999), Report 386 Calibration of LRFD Bridge Design Code, Transportation Research Board, National Academy Press.
3. Ayyub, Bilal M. (1998), Uncertainty Modeling and Analysis in Civil Engineering, CRC Press LLC.
4. Cho, H. N., Lim, J. K. and Choi, H. H. (2001), Reliability-based fatigue analysis for causes assessment of al collapsed steel truss bridge, Engineering Failure Analysis, Vol.8, Issue 4. pp.311~324.
5. Nowak, A.S. Yamani, A.S., and Tabsh, S.W. (1994), Probability Models for Resistance of Concrete Bridge Girders, ACI Structural Journal, Vol. 91, No, 3, pp.269~276.
6. Seoul Regional Construction Management Office (1992), Collapse Cause Assessment and Counterplan of Hang-Ju Grand Bridge Construction : Final Report.