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동특성 추정 기법과 신뢰성 해법에 의한 기설교량의 내하력 판정 방법

A RELIABILITY-BASED CAPACITY RATING OF EXISTING BRIDGES BY INCORPORATING SYSTEM IDENTIFICATION

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ABSTRACT

This paper develops practical models and methods for the assessment of safety and rating of damaged and/or deteriorated bridges by incorporating a system identification technique for the explicit inclusion of the degree of deterioration or damage and of the actual bridge response. And, based on the proposed model, reliability-based rating methods are proposed as LRFR(Load and Resistance Factor Rating) and system reliability-index rating criteria. The proposed limit state model explicitly accounts for the degree of deterioration or damage in terms of the damage and response factors. The damage factor in the paper is proposed as the ratio of the current stiffness to the intact stiffness.

Based on the observation and the results of applications to existing bridges, it may be concluded that the proposed rating models, which explicitly account for the uncertainties and the effects of degree of deterioration or damage based on the system identification technique, provide more realistic and consistent safety-assessment and capacity- rating.

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1. Introduction

In spite of the remarkable advances in structural modeling, numerical analysis and nondestructive testing, it is still difficult to predict realistic failure behavior and capacity-rating of existing road bridges, especially when those bridges are deteriorated or damaged to a significant degree. Recently, this has led to an increasing attention to the problems of safety assessment and rating of existing bridges, as well as the identification of the degree of deterioration or damage of those bridges in connection with the maintenance and rehabilitation problems.

This paper develops practical models and methods for the assessment of safety and rating of damaged and/or deteriorated bridges by incorporating such an elaborate technique as system identification or more approximately FFT analysis for the explicit inclusion of the degree of deterioration or damage and of the actual bridge response. And, based on the proposed model, reliability-based rating methods are proposed as LRFR(Load and Resistance Factor Rating) and system reliability-index rating criteria.

2. Limit State Model for Deteriorated or Damaged Bridges

For the development of a probability-based LRFR criteria [1] a linear limit state function for a structure may be used and stated as

$$g(\cdot) = R - \sum_i S_i \tag{1}$$

where, R is the structural resistance, S_i is the ith load effect.

A realistic safety assessment or rating of existing bridges requires a rational determination of the degree of deterioration or damage. Therefore, the limit state function, Eq.1, must incorporates some random variates to reflect such deterioration/damage and the underlying uncertainties. Various approaches, such as system identification

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[7,8], fuzzy set theory[9] or probabilistic measure of structural redundancy have been suggested[2]. A rational approach utilizing the system identification[3] for the damage assessment of structural members are proposed herein for practical application. However, in lieu of such elaborate techniques as system identification, the resistances of the deteriorated or damaged members are made to be estimated on the basis of visual inspection and/or simple in-situ tests with a practical analysis utilizing the FFT technique, supplemented with the engineering judgement.

The true resistance R may be modeled as,

$$R = R_n \cdot D_F \cdot N_R \qquad (2)$$

where R_n = the nominal resistance of the intact member in which the material strengths of the resistance are assumed as the real nominal values estimated on the basis of the NDT test results if available; D_F = the damage factor, which is the ratio of the current stiffness, K_D, to the intact stiffness, K_I = K_D / K_I ($\approx \omega_D^2 / \omega_I^2$) in which ω_D and ω_I are the fundamental natural frequencies of the damaged and the intact structures; and N_R = the correction factor for adjusting any bias and incorporating the uncertainties involved in the assessment of R_n and D_F. The mean-value of N_R represents the bias correction, and its C.O.V. represents the uncertainties in the material strength, fabrication, construction, structural modeling, and damage assessment.

For the rating purpose, the proposed load model needs to consider only the dead load and truck loads as the primary loadings for short span bridges. Thus, the load effects may be expressed as:

$$S = C_D \, D_n \, N_D + C_L \, L_n \, K \, N_L \qquad (3)$$

where C_D,C_L = the influence coefficients for dead and live load effects, which are estimated based on the current stiffness parameters of the deteriorated or damaged bridges ; D_n,L_n = the nominal dead and truck loads, respectively; K = the response ratio equal to K_S(1+I) in which K_S is the ratio of the measured stress to the calculated stress and I is the impact factor, either measured or calculated; and N_D,N_L = the correction factors for adjusting the bias and uncertainties in the estimated D_n and L_n, respectively.

In Eq.3 the uncertainties in the load effect model should include those associated with the analysis, load distribution, traffic load model and load test. Also, the random live-load effect should be evaluated on the basis of the current stiffness parameters of the deteriorated or damaged bridges, and the actual or estimated response ratio of the measured stress to the calculated one.

3. Damage Assessment by System Identification

For the purpose of capacity rating of existing bridge structures, which might have experienced significant structural damage through years of service, the structural damage may be approximately modeled as a reduction of the stiffness of a critical element[11] as

$$D^{(e)} = K_o^{(e)} - K^{(e)} = \sum \alpha_e \, K_o^{(e)} \qquad (4)$$

where $K^{(e)}$ and $K_o^{(e)}$ are the element stiffness matrices with and without damage, respectively; and α_e is the element coefficient($-1 < \alpha_e < 0$). For the cases of reinforced concrete bridges, it may be represented by a reduction of the stiffness of a critical element as

$$D_F = \frac{(EI)^{(e)}}{(EI)_o^{(e)}} \qquad (5)$$

In this study, the identification of the reduction of the element stiffness due to structural damage is carried out by two steps as follows;

(1) Determination of modal properties : The first few natural frequencies and the corresponding vibrational modes of the damaged structure are evaluated based on the dynamic response records measured at several locations of the structure. The extended Kalman filtering algorithm[3] has been applied to the estimation of the modal parameters. For this purpose, a state vector is defined by including the unknown parameters as the augmented state variables and nonlinear state equation is constructed from the equation of motion.

(2) Determination of structural damage : Comparing the estimated modal quantities with those of the undamaged structure, the location and degree of damage are determined with an aid of the inverse modal perturbation technique[11] :

$$[T][P^{(k)}]\{\alpha\} = \begin{Bmatrix} \mu_{ok}(\omega_k^2 - \omega_{ok}^2) \\ \beta\{\phi\}_k \end{Bmatrix} \qquad (6)$$

where $\{\alpha\}$ is the vector for the unknown element damage coefficient; [T] and $[P^{(k)}]$ are the transformation and modal perturbation matrices associated with the k-th mode, which are obtained in terms of the known or measured quantities; ω_{ok} and μ_{ok} are the k-th natural frequency and generalized mass of the undamaged structure; ω_k and $\{\phi\}_k$ are the k-th natural frequency and mode shape of the damaged structure which are measured; and β is the unknown scale factor of the measurement value of $\{\phi\}_k$. The unknown damage coefficient vector $\{\alpha\}$ is evaluated by way of minimizing the estimation error.

4. Reliability Assessment of Existing Bridges

An existing bridge structure may be rated on the basis of a specified target reliability. This requires the assessment of the reliability of a bridge in either element-reliability or system-reliability level. Obviously, system reliability is more desirable for the rating purpose regardless of the degree of the modeling accuracy or numerical approximations involved in the assessment. For this reason, the stable configuration approach (SCA)[4] is used to provide a practical and approximate method for estimating the system reliability against ultimate collapse of R.C. bridges, which may be considered to be a brittle mode of failure for which the SCA is particularly effective. Of course, for steel girder bridges that fail in ductile mode, the failure mode approach (FMA) considering only a few dominant failure modes may be more desirable and can be used without any further numerical difficulties. For the purpose of bridge rating, a second order bound estimate based on the approximate formulation of SCA or FMA is preferred to more elaborate theoretical formulation. A computer code developed based on the approximate SCA formulation of system reliability and the AFOSM method incorporating the equivalent-normal transformation and Haosfer-Lind's iterative algorithm are used for a practical evaluation of the system reliability index $\beta_s = -\Phi^{-1}(P_F)$. Then, using the reliability index as a requirement for structural safety, the values of β_s are suggested as a guide for developing rating criteria of deteriorated and/or damaged bridges.

5. Reliability-Based Rating Criterion

A load and resistance factor rating(LRFR) criterion may be developed corresponding to a specified target reliability index. Based on Eqs.2 and 3, the following rating criterion expressed in terms of the rating factor, RF, which is the ratio of the nominal load carrying capacity, Pn, to the standard rating load, PL, specified in the code may be obtained:

$$RF = \frac{P_n}{P_L} = \frac{\phi' D_F R_n - \gamma'_D C_D D_n}{\gamma'_L C_L K P_L} \qquad (7)$$

For the rating of an existing deteriorated bridges, the following two load levels of capacity rating of Eq.7 may have to be provided. At the service or lower level, the capacity rating may be referred to as the Service Load Rating(SLR) which corresponds to the allowable safe load level for the normal operation of the bridge. At the over-load or higher load level, the capacity rating may be referred to as the Maximum Over-Load Rating(MOR) which corresponds to the absolute permissible load level for special operation(over-load permit) of the bridge. The nominal safety parameters, ϕ', γ'_D and γ'_L, of the LRFR criterion of Eq.7 for each load level, SLR or MOR, corresponding to a specified target reliability (tentatively, β_o = 3.0 for SLR, β_o = 2.0 for MOR) may be calibrated by using the well established procedure for code calibration[5].

For the assessment of reliability of existing bridges and the calibration of rating criterion, the statistical uncertainties of resistance and load effects are estimated from the data available in Korea[6] and partly from the engineering judgement. As the results of the calibration, the proposed LRFR criteria are shown in Table 1, which is given as in the form of the rating provisions for R.C. T-beam and slab bridges.

6. Application Examples

6.1 Damage Assessment

At first, an example analysis is carried out by using records generated by the simulation technique in order to verify the present method of the damage estimation. The structural model used is a R.C. beam with a uniform T-section as in Fig 1. Four different cases with damages at single or multiple locations are investigated. It is assumed that response time histories due to an impact load applied at Node 7 are measured at four nodes, i.e., Nodes 4,5,6 and 7. The first three natural frequencies and the first mode shape for each case are determined from the response time histories by using the extended Kalman filtering technique. Then, the element damage coefficients are estimated by the inverse modal perturbation. Table 2 summaries the assumed exact and the estimated values for the element damage coefficients. The results indicate that the present method can identify the locations of the damages very precisely. The accuracy of the estimated degree of damage has been founded to be somewhat deteriorated, but still remains in a reasonable range. Currently, experimental studies are being carried out to verify the applicability of the method to real structures.

6.2 Reliability Assessment

The models and methods of reliability analysis using the stable configuration approach and the AFOSM algorithm proposed in the paper are applied for the reliability-assessment of three existing R.C. T-beam bridges which were field-tested for the safety-evaluation and capacity rating. Table 3 summarizes the bridge data obtained from the measurements and calculations performed for the safety-assessment of these bridges. The results of reliability evaluation in terms of the element-reliability and system-reliability indices of the example bridges are shown in Table 4.

The data summarized in Table 3 as well as the visual inspections of these bridges indicate that the bridges are significantly deteriorated and/or damaged. Accordingly, the estimated reliability indices are found to be remarkably low for the bridges as shown in Table 4. It has to be noted that the low reliability indices of the bridges result also from the fact that the current rating load used for safety assessment is higher than the original design load. It may be also observed that the estimated system-reliability indices are consistently higher than the results for the element-reliability in spite of the fact that the system reliability evaluated based on the SCA method is an approximate conservative estimate. It may be argued that the system reliability index may have to be used, if possible, rather than the element-reliability index in order to take into account some reserved safety related to the redundancy of the bridge system. Furthermore, the results of the reliability evaluation as compared with the rating factors discussed in the following section, indicated that the reliability index may be used as a preliminary measure of the rating of existing bridges with only visual inspection before performing extensive field measurement.

6.3 Reliability-Based LRFR Criterion

The recommended provisions of LRFR criterion as in Table 1 are applied for the rating of the bridges discussed in the previous section. As the rating vehicle for the LRFR criterion, the DB-24 which is the standard design-truck of the KSCE bridge design code is used. The DB-standard trucks are similar to the AASHTO's standard design trucks. Note that, for example, the configurations of D-18 and DB-18 of the KSCE correspond to those of H-20 and HS-20 of the AASHTO. The combined weight on the first two axles of DB-18 is 18 tons which corresponds to 20 short-tons of HS-20. A comparison of the results between the proposed LRFR rating and the conventional rating such as WSR, LFR and the AASHTO rating is presented in Table 4. The results indicate that there are strong coherences between the estimated values for the SLR-rating factors and the reliability indices, which vary depending on the state of damage and/or deterioration of the bridges. It may be observed from Table 5 that, in general, the results of the conventional rating methods are not considerably different from those of the LRFR method for these particular bridges, although there are still some significant differences between the results of the proposed LRFR rating and those of the conventional ratings. However, considering that the current WSR or LFR criterion could result in rather irrational ratings because of inherent shortcomings in the conventional criteria which do not account for all the underlying uncertainties and the degree of the deterioration and damage, and thus are not reliability based, the results of the LRFR may be regarded as more rational ratings. It is interesting to observe that the rating of each example bridge at SLR and MOR levels are somewhat similar to those of the AASHTO rating although the AASHTO rating specification is not reliability-based. However, as stated above, the differences between the proposed and the conventional ratings may, mainly, be attributed to the fact that the proposed LRFR do explicitly account for the degree of the deterioration and damage in terms of the damage factor and the safety factors, ϕ, γ_i , which are derived on the basis of the reliability methods. Furthermore, it may be noted that the results of rating of each example bridge reasonably well correspond to the reliability indices presented in Table 4.

7. Conclusions

Based on the observation and the results of the application, it may be concluded that the proposed rating models, which explicitly account for the uncertainties and the effect of the degree of deterioration or damage based on the system identification or FFT analysis, provide more realistic and consistent safety-assessment and capacity-rating. Thus, it is strongly recommended that the system reliability index β_s and LRFR rating, rather than the conventional WSR or LFR rating, be preferably used in practice for the realistic assessment of safety and remaining reserved capacity of deteriorated and/or damaged bridges.

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Table 1. LRFR-Rating Criteria

Bridge	SLR	MOR
R.C. T-beam	$\dfrac{0.80D_F R_n - 1.20C_D D_n}{1.85C_L K P_L}$	$\dfrac{0.95D_F R_n - 1.20C_D D_n}{1.65C_L K P_L}$
R.C. slab	$\dfrac{0.85D_F R_n - 1.20C_D D_n}{1.85C_L K P_L}$	$\dfrac{1.00D_F R_n - 1.20C_D D_n}{1.65C_L K P_L}$

Table 2. Exact and Estimated Damage Coefficient(α_e)

Cases	El. No.	Assumed Exact α_e	Estimated α_e	Nat. Freq.(Hz) ($\omega_1, \omega_2, \omega_3$)
damage I	3		0.0	
	4		0.0007	60.1
	5	0.4	0.5810	257.0
	6		0.0006	547.0
	7		0.0001	
damage II	3	0.4	0.5380	
	4		0.0030	58.0
	5	0.4	0.5361	242.0
	6		0.0037	536.0
	7		0.0	
damage III	3	0.4	0.5210	
	4		0.0	56.8
	5	0.4	0.5206	238.0
	6	0.2	0.1956	533.0
	7		0.0021	
damage IV	1	0.4	0.5970	
	4		0.0016	58.7
	5	0.4	0.5549	250.0
	6	0.2	0.2093	534.0
	7		0.0	
damage V	3	0.2	0.2202	
	4		0.0	60.4
	5	0.2	0.2202	247.0
	6	0.2	0.2205	557.0
	7		0.0	
damage VI	1	0.3	0.4178	
	4		0.0010	61.1
	5	0.2	0.2257	252.0
	6	0.2	0.2266	554.0
	7		0.0	

Note: Natural Frequencies of the undamaged structure (in Hz)
$\omega_{o1} = 64.3$, $\omega_{o2} = 257.5$, $\omega_{o3} = 578.8$

Table 3. Bridge Data(R.C. T-beam)

Bridge	Jinjeon	Wolcheon	Seosang
Design Load	D-9	D-13.5	D-13
Construction Year	1932	1956	1957
Rating Load	DB-24	DB-24	DB-24
No. of Girder	6	3	4
Girder Space(cm)	127	195	110
Span Length(cm)	1000	1400	1100
M_N (t-m)	64.2	226	123
M_D (t-m)	24.5	87.5	29.8
M_L (t-m)	10.4	35.9	37.5
D_F	0.75	0.89	0.86
$\sigma_{cal} / \sigma_{test}$	3.35	1.64	1.22
$(1+i_c)/(1+i_t)$	0.90	1.17	1.05
δ_c / δ_t	1.22	4.48	5.28
K	1.06	0.69	1.03
S_{Dn}(t-m)	24.5	87.5	29.8
S_{Ln}(t-m)	11.02	24.59	38.63
1+I	1.3	1.12	1.26

Table 4. Reliability of Bridges

Bridge	Jinjeon	Wolcheon	Seosang
Element-Rel.	1.42*	2.87*	1.64**
System-Rel.	1.81	3.70	2.19

Note: *: at Internal Girder
**: at External Girder

Table 5. Rating of Bridges

Bridge		Jinjeon	Wolchcon	Seosang
LRFR	SLR	0.45	1.24	0.68
	MOR	0.90	2.13	1.01
WSR		0.48	1.02	0.54
LFR	0.52	1.37	0.72	
AASHTO	I.RF	0.48	1.27	0.67
	O.RF	0.80	2.12	1.12

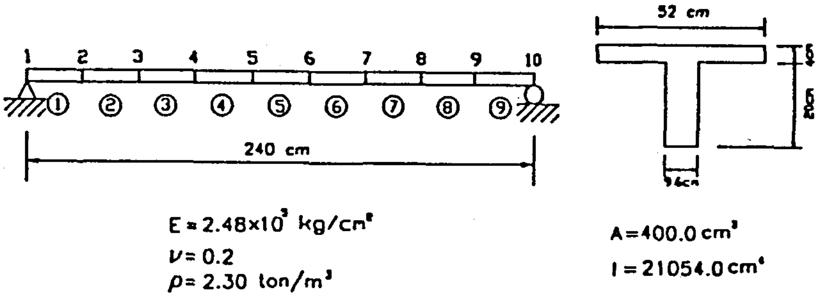

Fig.1. Structural model of R.C. beam with a uniform T-section.