

# ASSESSMENT OF SYSTEM RELIABILITY AND CAPACITY-RATING OF COMPOSITE STEEL BOX-GIRDER HIGHWAY BRIDGES

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This paper develops practical and realistic reliability models and methods for the evaluation of system-reliability and system reliability-based rating of various types of box-girder bridge super-structures. The results of the reliability evaluation and rating of existing bridges indicate that the reserved reliability and capacity rating at system level are significantly different from those of element reliability or conventional methods especially in the case of highly redundant box-girder bridges.

**Key Words :** *interactive limit state function, system reliability, probabilistic system redundancy factor, probabilistic system reserve factor, capacity-rating.*

## 1. INTRODUCTION

The optimal decision on the bridge maintenance and rehabilitation involves tremendous economic and safety implication, and heavily depends upon the results of the evaluation of residual safety and carrying-capacity of the existing bridges. However, in spite of the remarkable advances in modelling and numerical or analytical techniques for response or behavior analysis and ultimate strength or stability analysis of redundant bridge system such as steel box-girder bridges, it is still extremely difficult to evaluate realistic residual system-safety or system carrying-capacity especially when these bridges are deteriorated or damaged to a significant degree.

It has to be noted that the cross beams and diaphragms as well as concrete decks of box-girder bridge significantly contribute to transverse load distribution and redundancy, and also effectively provide the resistance to eccentric loads. Thereby, the capacity rating and safety evaluation of box-girder bridges based on system performance and system reliability are very important for the realistic prediction of residual carrying capacity of these highly redundant bridge system.

Recently, some practical system reliability models and methods for I-girder bridges<sup>(1,8),(10)</sup> have been suggested with the emphasis on the system-level reliability rather than the element level. Also some practical approaches for reliability based

safety assessment and capacity rating have been made by Cho and Ang<sup>2)</sup>.

Various approaches to system redundancy measure have been proposed by several researchers<sup>3)</sup>. However, no established practical approaches to the assessment of system redundancy or system reliability are available especially for continuous, composite and multi-box steel girder bridges.

This paper develops practical reliability models and methods for the evaluation of system reliability and proposes a new method for the system reliability-based redundancy and capacity-rating that incorporate the concept of non-codified equivalent system-capacity of existing bridges.

## 2. LIMIT STATE MODEL

### (1) Element Limit State Model

Since this study is concerned with the ultimate carrying-capacity of existing steel box-girder bridges, the ultimate limit state functions need to be considered in the modelling. The strength limit state models at element level for box-girder bridges suggested in the paper are based on the basic flexural strength as well as the strength interaction equations which simultaneously take into account flexure, shear and torsion.

#### a) Bending Strength Limit State Model

When the primary bending failure alone is considered, the linear bending strength equation becomes,

$$g(\cdot) = M_R - (M_D + M_L) \dots\dots\dots (1)$$

where  $M_R$  = true moment strength ;  $M_D$ ,  $M_L$  = true applied moment. A realistic safety assessment or rating of existing bridges requires a rational determination of the degree of deterioration or

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damage. Therefore, the true moment strength  $M_R$  in Eq.(1) must incorporate some random variates to reflect such deterioration/damage and the underlying uncertainties. System identification techniques<sup>13)</sup> may be used for the precise evaluation of the damage factor,  $D_F$ , proposed in the paper. 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 techniques, supplemented with the engineering judgement. The true moment strength  $M_R$  may be modelled as,

$$M_R = M_n N_M D_F \dots\dots\dots (2)$$

where  $M_n$ =nominal moment strength specified in the code ;  $N_M$ =the correction factor adjusting any bias and incorporating the uncertainties involved in the assessment of  $M_n$  and  $D_F$  ( $=MFPD$ ), in which,  $M$ =material strength uncertainties ;  $F$ =fabrication and construction uncertainties ;  $P$ =prediction and modelling uncertainties ;  $D$ =the uncertainties involved in the assessment of damages and/or deterioration ;  $D_F$ =the damage factor, which is the ratio of current stiffness,  $K_D$ , to the intact stiffness,  $K_I$ , i.e.  $K_D/K_I (\cong \omega_D^2/\omega_I^2)$  in which  $\omega_D$  and  $\omega_I$  are the fundamental natural frequencies of the damaged and the intact structures.

It may be noted that the nominal moment strength  $M_n$  specified in the code becomes either yield moment  $M_y$  in case of tension failure or buckling moment  $M_{cr}$  in case of compression failure.

Also, true applied moments  $M_D$ ,  $M_L$  may be expressed in terms of respective random variate as follows,

$$M_D = m_D D_n N_D \dots\dots\dots (3a)$$

$$M_L = m_L L_n K N_L \dots\dots\dots (3b)$$

where  $m_D$ ,  $m_L$  = the influence coefficients of moment for dead and live loads ;  $D_n$ ,  $L_n$ =the nominal dead and live loads ;  $K$ =response ratio =  $K_s(1+I)$  ;  $N_D$ ,  $N_L$ =correction factors ( $=AQ$ ), in which,  $K_s$ =the ratio of the measured stress to the calculated stress ;  $I$ =the impact factor ;  $A$ =response random variables corresponding to dead or live loads ;  $Q$ =random variable representing the uncertainties involved in dead or live loads.

**b) Interactive Failure Limit State Model**

When the interaction type of combined failure limit state function needs to be considered, the interaction stress or strength failure limit state in terms of bending, shear and torsion may be used in the form of the code specified interaction equation without applying the safety factors. The interaction failure criteria specified in both Korean and

Table 1 Statistical uncertainties			
Variables	$\bar{X}/X_n$	$\Omega_x$	Dist.
Resistance	1.08	0.15	log-normal
Dead load effect	1.05	0.10	normal
Live load effect	1.15	0.19	log-normal

Japanese Standard Bridge Codes are based on the maximum distortion energy theory<sup>11)</sup>. Thus, the nonlinear limit state function may be stated as follows,

$$g(\cdot) = 1.0 - \left\{ \left( \frac{\sigma_D + \sigma_L}{\sigma_R} \right)^2 + \left( \frac{\tau_D + \tau_L}{\tau_R} \right)^2 \right\} \dots\dots (4)$$

where  $\sigma_R$ ,  $\tau_R$ =true ultimate or critical bending and shear stress ;  $\sigma_D$ ,  $\sigma_L$ ,  $\tau_D$ ,  $\tau_L$ =true bending and shear stress, respectively.

Also in the similar form as Eq.(2),  $\sigma_R$  and  $\tau_R$  may be given as follows,

$$\sigma_R = \sigma_n N_\sigma D_F \dots\dots\dots (6a)$$

$$\tau_R = \tau_n N_\tau D_F \dots\dots\dots (5b)$$

where  $\sigma_n$ ,  $\tau_n$ =nominal ultimate bending and shear stress specified in the code ;  $N_\sigma$ ,  $N_\tau$ =correction factors ;  $D_F$ =damage factor.

Again,  $\sigma_D$ ,  $\sigma_L$ ,  $\tau_D$  and  $\tau_L$  may be expressed as,

$$\sigma_D = \underline{\sigma}_D D_n N_{D\sigma} \dots\dots\dots (6a)$$

$$\sigma_L = \underline{\sigma}_L L_n K N_{L\sigma} \dots\dots\dots (6b)$$

$$\tau_D = \underline{\tau}_D D_n N_{D\tau} \dots\dots\dots (6c)$$

$$\tau_L = \underline{\tau}_L L_n K N_{L\tau} \dots\dots\dots (6d)$$

where  $D_n$ ,  $L_n$ =nominal dead and live loads ;  $\underline{\sigma}_D$ ,  $\underline{\sigma}_L$ ,  $\underline{\tau}_D$ ,  $\underline{\tau}_L$ =the influence coefficients of bending and shear stress for dead and live loads ;  $N_{D\sigma}$ ,  $N_{L\sigma}$ ,  $N_{D\tau}$ ,  $N_{L\tau}$ =correction factors.

**(2) Mechanism Failure Limit State Model**

For the system reliability analysis based on the collapse mechanism of box girder bridges, the following limit state of failure mechanisms may have to be used,

$$g_i(\cdot) = \sum_j c_{ij} M_{Rij} - \sum_k (b_{Dik} S_{Dik} + b_{Lik} S_{Lik}) \dots\dots\dots (7)$$

where  $M_{Rij}$ =true moment strength of  $j$  th section in  $i$  th mechanism ;  $S_{Dik}$ ,  $S_{Lik}$ =true applied load effects of  $k$  th loading in  $i$  th failure mechanism ;  $c_{ij}$ ,  $b_{Dik}$ ,  $b_{Lik}$ =coefficients that describe a collapse mode. The true resistance  $M_{Rij}$  and applied load effects  $S_{ik}$  may be modelled in the same way as Eq.(2) and (3).

**(3) Statistical Uncertainties**

In the paper, all the uncertainties of the basic random variables of resistance and load effects described above are obtained from data available in the literature<sup>4),12)</sup>. The mean-nominal ratio and COV of resistance and load effects with the

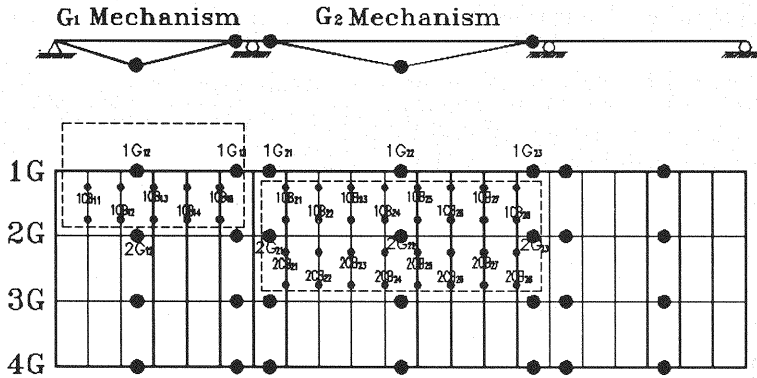


Fig.1 Collapse failure state of box-girder bridge

assumed distributions are summarized in Table 1.

### 3. SYSTEM RELIABILITY

#### (1) Reliability Analysis

The structural reliability may be conceptually measured or numerically evaluated by the failure probability,  $P_F$ . However practically, relative reserve safety of a structural element or system may be best represented by the corresponding safety index  $\beta$ , i.e.,

$$\beta = -\Phi^{-1}(P_F) \dots\dots\dots (8)$$

where  $P_F$ =probability of failure ;  $\Phi^{-1}$ =inverse of the standard normal distribution function.

Various available numerical methods can be applied for the reliability analysis of the bridges at either element or system level using the limit state models proposed in the paper. For the evaluation of element reliability, the AFOSM method<sup>4)</sup> incorporating the equivalent-normal transformation and Hasofer-Lind's iterative algorithm is used for bending limit state function, but an improved IST (Importance Sampling Technique) algorithm which is implemented as a computer code developed by the author<sup>3)</sup> is used for the system reliability and interactive failure limit state analysis of the proposed models. The proposed IST algorithm for the computation FMA(Failure Mode Approach) of system failure (10a) probability  $P_{F(syS)} (= \int_X I[X] [f(x)/h(x)] dx)$  concerned with  $h(x)$  is based on the following proposes importance sampling scheme,

$$h(x) = \sum p_i h_i(x) \dots\dots\dots (9a)$$

$$p_i(x) = \frac{f_i(x^*)}{\sum f_i(x^*)} \dots\dots\dots (9b)$$

where  $x$ =basic random variables ;  $x^*$ =MLF(Maximum Likelihood Failure) point ;  $I[X]$ =indicator function ;  $f(x)$ =joint probability density function of  $x$  ;  $h(x)$ =sampling density function proposed as a form of the composition density function ;

$p_i$ =probability or relative weight associated with  $h_i(x)$ , the  $i$ -th sampling density of  $i$ -th failure mode. It may be noted that the introduction of  $h(x)$  is to locate more samples on more important regions of  $x$  which could make significant contributions of  $P_{F(syS)}$ . As it is demonstrated in the references<sup>7)</sup> the main advantage of using the IST may be attributed to the fact that the difficulties associated with the intractable problems such as interactive non-linear limit state functions, correlated non-normal variates and complexity or generality of reliability model do not appear to exist with the IST simulation and thus do not seem to significantly affect the convergence rate or result.

#### (2) Practical System Reliability Assessment for Box-Girder Bridges

Obviously, the failure of a single element or member does not constitute a system failure of highly redundant bridge system such as steel box-girder bridges. As such, the collapse failure of a bridge-system is significantly different from element failures.

The realization of collapse failure state of an existing bridge may be defined as the limit state of system performance. Various descriptions for system failure or system resistance are possible based on either theoretical or practical approaches. Nowak<sup>10)</sup> defined the system failure of girder type bridges as the attainment of either a prescribed large amount of permanent deformation or unstable singular system stiffness matrix, for which he used an incremental nonlinear analysis of grid model. However, in this study for the practical but efficient numerical solution of system reliability without involving extensive nonlinear structural analysis, it is assumed that the system failure state of box-girder bridge may be defined as the realization of collapse mechanism of major girders with or without considering the contribution of deck and cross beams. For this approach, an assumption is also made for the modelling of limit

state such that approximate pseudo- mechanism analysis is possible by taking the critical buckling moment in compression failure zone or the yield moment in tension failure zone as the ultimate moment of box-girder section as shown in Fig.1. And thus, the system reliability problem of box-girder super-structure is formulated as parallel (mechanism)-series models obtained from the FMA (Failure Mode Approach) based on major failure mechanisms. Fig.1 shows a typical illustrative example of some failure mechanisms of grid model for a 3-span continuous box-girder bridge.

The system modelling of steel box-girder bridge can be made either by considering or neglecting the contribution of cross beams to ultimate strength of mechanisms. Also, it may be noted that at element reliability level the load effect of each girder is obtained from the linear elastic analysis of grid model for box-girder bridges.

(3) Probabilistic System Redundancy and Reserve Safety

The collapse of a bridge occurs by taking multiple failure paths involving various intermediate damage or failure state after initial failure. Thus, the definition of system redundancy requires a measurement of the ultimate capacity of a bridge to resist collapse failure following the initial element failure.

Thereby, the results of system-reliability analysis in terms of system reliability index may be effectively used either as a probabilistic measure of system redundancy or reserve safety of existing bridges. So far, various approaches to the definition for the measure of the system redundancy or reserve safety have been suggested by several researchers<sup>(5),(9)</sup>.

The following definitions for system redundancy and reserve safety in terms of reliability indices are adopted in the paper as a measure of system redundancy and reserve safety<sup>(6)</sup>.

PSRF=β<sub>s</sub>/β<sub>i</sub>..... (10a)

PSReF=β<sub>s</sub>/β<sub>e</sub>..... (10b)

where PSRF=Probabilistic System Redundancy Factor ; PSReF= Probabilistic System Reserve Factor ; β<sub>s</sub>=system reliability index ; β<sub>i</sub>=reliability index of initial-failure element ; β<sub>e</sub>=element reliability index.

Because, this study is primary concerned with the capacity rating of existing box-girder bridges PSReF will preferably be used in the numerical application.

4. SYSTEM RELIABILITY-BASED RATING

The conventional capacity rating of a bridge have

Table 2 Load and resistance factor for rating of steel girder bridges

Target Rel.	φ '	γ <sub>D</sub> '	γ <sub>L</sub> '
β <sub>sol</sub> =3.0(SLR)	0.85	1.20	2.0
β <sub>sol</sub> =2.5(MOR)	0.95	1.20	1.7

been largely based on the WSR (Working Stress Rating) or LFR (Load Factor Rating) criterions which do not systematically take into account any information on the uncertainties of strength and loading, the degree of damage or deterioration, and the characteristics of actual response or redundancy specific to the bridge to be rated. Thus, unfortunately the nominal rating load or reserve capacity evaluated by the conventional code-specified formula, in general, fails to predict realistic carrying capacity or reserve capacity of deteriorated or damaged bridges. Recently, Moses<sup>(9)</sup> and the authors<sup>(12)</sup> have suggested reliability index to be used as a rating criterion to predict realistic relative reserve safety by incorporating actual bridge conditions and uncertainties.

For more realistic capacity rating utilizing the reserve safety of redundant bridge such as box-girder bridges, the system reliability index is suggested to be used as a β-rating criterion. Also, this paper proposes a practical but rational approach for the evaluation of capacity-rating load (P<sub>n</sub>) or rating factor (RF) in the form of the equivalent system-capacity rating, which is derived based on the concept of FOSM form of system reliability index. For a comparative study with the codified LRFR (Load and Resistance Factor Rating) criteria previously developed by the author<sup>(12)</sup>, the LRFR criteria will also be given herein.

(1) Codified LRFR Criteria

The following general LRFR criterion may be developed corresponding to a specified target reliability index<sup>(2)</sup>.

P<sub>n</sub>=φ'D<sub>F</sub>R<sub>n</sub>-γ'<sub>D</sub>C<sub>D</sub>D<sub>n</sub>..... (11)

RF=P<sub>n</sub>/P<sub>r</sub>..... (12)

where P<sub>n</sub>=the nominal load carrying capacity ; P<sub>r</sub>=the standard design or rating load ; φ', γ'<sub>D</sub>, γ'<sub>L</sub>=the nominal resistance, dead load and live load factors, respectively ; R<sub>n</sub>=nominal strength specified in the code, which becomes M<sub>n</sub> of Eq.(2) in the case of flexural limit state ; c<sub>D</sub>, c<sub>L</sub>=unit mean dead and live load effects, which are also identical with m<sub>D</sub>, m<sub>L</sub> of Eq.(3a, b), in the case of flexural limit state.

The results of calibration for steel girder bridges

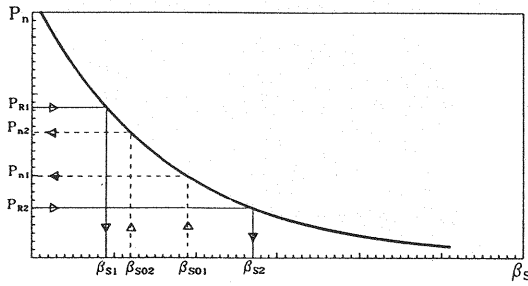


Fig.2  $\beta_s$  versus  $P_n$

corresponding to SLR (Service Load Rating,  $\beta_{c01}=3.0$ ) and MOR (Maximum Overload Rating,  $\beta_{c02}=2.5$ ) are shown in Table 2.

## (2) Non-Codified System-Reliability-Based Equivalent-Capacity Rating

The system reliability index  $\beta_s$  may be conceptually expressed as the ln-ln model of the FOSM form of 2nd moment reliability methods in the following way,

$$\beta_s \cong \frac{\ln(\bar{R}_s/\bar{Q}_s)}{\sqrt{\Omega_{R_s}^2 + \Omega_{Q_s}^2}} \quad (13)$$

where  $\bar{R}_s$ =mean system resistance ; and  $\bar{Q}_s$ =mean system load effects,  $\Omega_{R_s}$  and  $\Omega_{Q_s}$ =the COV of system resistance and load effects. And  $\bar{Q}_s$  may be expressed in terms of system mean dead and live load effects ( $\bar{Q}_s = \bar{c}_{Ls}P_n + \bar{c}_{Ds}D_n$ ), Ep.(13) may be solved for  $P_n$  as follows ;

$$P_n = Z_m \text{EXP}(-\beta_s \Omega_s) - \eta_s D_n \quad (14)$$

where  $Z_m$ =parameter that conceptionally represents the mean resistance safety ratio ( $\bar{R}_s/\bar{c}_{Ls}$ ) ;  $\Omega_s = \sqrt{\Omega_{R_s}^2 + \Omega_{Q_s}^2}$ =parameter that conceptionally represents the system uncertainties ;  $\eta_s$ =ratio of unit system mean dead and live load effects( $=\bar{c}_{Ds}/\bar{c}_{Ls}$ ). As shown in Fig.2 the relationship between  $P_n$  and  $\beta_s$  can be graphically represented by the exponential curve corresponding to Eq.(14).

Thus, the unknown parameters  $Z_m$  and  $\Omega_s$  of Eq.(13) can be evaluated when the two distinct rating points( $P_{R1}, \beta_{s1}$ ) are substituted into Eq.(14). Note that these are obtained as the system reliability indices  $\beta_{s1}$  and  $\beta_{s2}$  corresponding to the upper and lower standard rating load  $P_{R1}$  and  $P_{R2}$ , respectively. Thus, Eq.(14) becomes

$$P_{R1} = Z_m \text{EXP}(-\Omega_s \beta_{s1}) - \eta_s D_n \quad (15a)$$

$$P_{R2} = Z_m \text{EXP}(-\Omega_s \beta_{s2}) - \eta_s D_n \quad (15b)$$

From Eq.(15a) and (15b) the parameters  $Z_m$  and  $\Omega_s$  can be derived as follows ;

$$Z_m = \left[ \frac{(P_{R2} + \eta_s D_n)^{\beta_{s1}}}{(P_{R1} + \eta_s D_n)^{\beta_{s2}}} \right]^{\frac{1}{\Delta\beta}} \quad (16)$$

$$\Omega_s = -\frac{1}{\Delta\beta} \ln \left( \frac{P_{R1} + \eta_s D_n}{P_{R2} + \eta_s D_n} \right) \quad (17)$$

Table 3 Comparisons with Nowak's evaluation

Approach	$\beta_s$	$\beta_s$
Nowak	3.80	4.95( $\rho=1$ ) 6.20( $\rho=0$ )
Proposed	3.80(Ext.G) 5.23(Int.G)	5.86

Table 4 Bridge data

Bridge	Sang-il	Ham-an
Type	Continuous box with 3 span	Continuous box with 3 span
Span Length	30.3+45.5+30.3 = 116.12 m	29.95+35+29.91 = 95 m
Design Load	DB-24, DB-18	DB-24
Girder Space	6.9m	5.0m
No. of Girder	4	2
$\sigma_{test}/\sigma_{cal}$	0.4826	0.6847
Material Type	SWS 50	SWS 50
Impact Factor	1.250(1,3 span) 1.211(2 span)	1.250(1,3 span) 1.232(2 span)
Damage Factor	1.0	1.0

where  $\Delta\beta = \beta_{s1} - \beta_{s2}$ .

Finally, substituting Eq.(16) and (17) into Eq.(14),  $P_n$  may be derived in the following form ;

$$P_n = \frac{(P_{R2} + \eta_s D_n)^{\Delta\beta_1/\Delta\beta}}{(P_{R1} + \eta_s D_n)^{\Delta\beta_2/\Delta\beta}} - \eta_s D_n \quad (18)$$

where  $P_n$ =nominal load carrying capacity ;  $P_{R1}$ ,  $P_{R2}$ =upper and lower rating loads, respectively ;  $\Delta\beta_1 = \beta_{s1} - \beta_{s0}$  ;  $\Delta\beta_2 = \beta_{s2} - \beta_{s0}$ , in which,  $\beta_{s1}$  and  $\beta_{s2}$ =system reliability indices corresponding to  $P_{R1}$  and  $P_{R2}$  respectively ;  $\beta_{s0}$ =target reliability.

The equivalent system-rating factor proposed in the paper is a new concept which enables the bridge engineers to easily understand the reserve carrying capacity of a bridge superstructure as system in terms of the maximum system-capacity rating load  $P_n$  at SLR ( $\beta_{s01}=3.0$ ) or MOR ( $\beta_{s02}=2.5$ ).

## (3) Deterministic System Redundancy and Reserve Strength

Once the ultimate system-capacity in terms of the equivalent system rating load  $P_n$  is obtained from Eq.(18) the deterministic measure of system redundancy and reserve strength corresponding to those of probabilistic measure may be defined as follows,

$$\text{DSRF} = P_{ns}/P_{ni} \quad (19a)$$

$$\text{DSReF} = P_{ns}/P_{ne} \quad (19b)$$

where DSRF=Deterministic System Redundancy Factor ; DSReF=Deterministic System Reserve Factor ;  $P_{ns}$ =nominal load of ultimate system capacity corresponding to system reliability index ;  $P_{ne}$ =nominal load of element capacity corresponding to element reliability index ;  $P_{ni}$ =nominal load of initial-failure capacity corresponding to reliability index of initial-failure element.

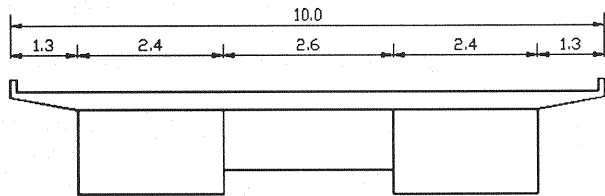


Fig.3 Cross section of Ham-an bridge (unit : m)

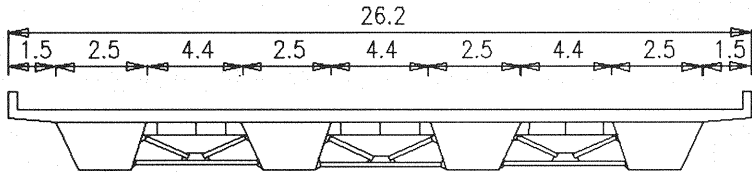


Fig.4 Cross section of Sang-il bridge (unit : m)

Table 5 Reliability of example bridges

Bridge	Element Reliability $\beta_e$ ( $P_F$ )		System Reliability $\beta_s$ ( $P_F$ )		Initial-Failure Reliability $\beta_i$ ( $P_F$ )
	Bending Strength Limit State	Interactive Failure Limit State	Without Cross beam Effect	With Cross beam Effect	
Sang-il (4-Box)	3.11 (0.9354E-3)	2.83 (0.2347E-2)	4.86 (0.5632E-6)	6.73 (0.1023E-10)	2.38 (0.8672E-2)
Ham-an (2-Box)	4.78 (0.9318E-5)	4.22 (0.1222E-4)	5.20 (0.9551E-7)	5.76 (0.4129E- 8)	3.93 (0.4242E-4)

Table 6 Capacity rating of example bridges

Basis-Capacity Rating	Method		Sang-il		Ham-an	
			$P_s(t)$	RF	$P_s(t)$	RF
System Reliability-Based	Non-Codified	SLR	140.9	3.26	184.9	4.28
		MOR	229.4	5.31	257.3	5.95
Element Reliability-Based	Non-Codified	SLR	95.5	2.21	147.3	3.41
		MOR	142.2	3.29	182.3	4.21
	LRFR	SLR	109.2	2.53	147.1	3.41
		MOR	155.6	3.60	200.0	4.63
	WSR		150.8	3.49	194.4	4.50
	LFR(AASHTO)	I. R	104.7	2.42	122.1	2.83
		O. R	174.5	4.04	203.5	4.71

Table 7 System redundancy and reserve safety/strength

Bridge		PSRF	PSReF	DERF	DSReF
Sang-il	• Without Cross beam effect	2.04	1.56	2.12	1.61
	• With Cross beam effect	2.83	2.16	3.01	2.03
Ham-an	• Without Cross beam effect	1.32	1.09	1.87	1.41
	• With Cross beam effect	1.47	1.21	2.06	1.61

5. APPLICATION

( 1 ) Applicability of the System Reliability Model

At first, the applicability of the proposed models

and methods for system reliability analysis is demonstrated by comparing the results for an illustrative example with those of the Nowak's approach<sup>(10)</sup>. The example bridge that Nowak used for system reliability evaluation was an 18-m composite steel girder bridge with 5 W 33 × 135 girder spaced at 2.4-m. It may be observed that at the element reliability level, two results are identical as expected, but at the system level, the results of the proposed method fall between the extreme results corresponding to the Nowak's assumed correlation, which apparently indicates the appropriateness of the proposed approach. Table 3 shows the results of element and system reliabilities evaluated by two approaches.

## (2) Example Bridges

The modelling and analysis methods for the system reliability proposed in this paper are applied to two existing steel-box girder bridges. Some of measured and analysis results with bridge data are given in Table 4.

## (3) System Redundancy and Reserve Safety/Strength

The results of the system redundancy measures based on the reliability assessment for the example bridges are summarized in Table 5 and 7. First of all, in Table 5 it can be clearly observed that considerable differences exist between the element and system reliabilities in the range of  $\Delta\beta=2.03\sim 3.9$ , and thus, in turn, it results in relatively high values in the measures of both probabilistic and deterministic system redundancy and residual safety/strength up to 2.16/2.83 for PSReF/PSRF, 2.03/3.01 for DSReF/DSRF for Sang-il Bridge. These results apparently indicate that the decks, cross beams and secondary members significantly contribute to the system redundancy. Therefore, it may be argued that system reliability approaches may have to be used for the evaluation of realistic reserve safety and capacity of highly redundant bridges. Next, as seen in Table 5, it may be noted that the element reliability based on the interactive failure limit state are significantly lower by 10~12% compared to those based on the bending strength limit state.

Furthermore, it can be noted in Table 7 that the effect of the number of girders on the system redundancy in the case of Sang-il bridge with 4 box-girders renders a lot more significant results with 1.56 for PSRF and 3.01 for DSRF in the case of Ham-an bridge with 2 box-girders. Also it can be seen from Table 5 that the system reliabilities based on the failure mechanism considering the effect of the cross beams are about 10~28% higher than those without considering it. Again, it may be emphasized that the cross beams significantly contribute to the collapse strength of the structure.

## (4) Rating of Example Bridges

The results of capacity rating of the example bridges are summarized in Table 6. As it has been already shown in the previous section with the discussion of the system reliability and redundancy, it can also be observed that the non-codified capacity ratings based on system reliability is a lot higher by 20~30% than non-codified or LRFR rating (with  $RF=2.21\sim 3.41$  for SLR,  $3.29\sim 4.21$  for MOR) based on the element reliability. It is also interesting to observe that the results of non-codified and LRFR capacity ratings are about similar. However, it can be seen that, at the element level, the conventional WSR provides

unreasonably higher results (with  $RF=3.49\sim 4.50$ ) than the reliability-based capacity rating, whereas the ASHTO-LFR rating gives almost similar results at the element level (with  $RF=2.42\sim 2.83$ ).

Based on these comparative observations, it may be suggested that the reliability and capacity-rating evaluated at the system level are significantly different from those evaluated at the element level, especially in the case of highly redundant box-girder bridges. Finally, it may be stated that the non-codified equivalent system-capacity formula derived on the basis of system reliabilities proposed in the paper can be successfully applied to assess the system-redundancy or reserved system-capacity of existing bridges in practice.

## 6. CONCLUSION

Because of the redundancy and effective load sharing provided by the decks and cross beams in composite steel box-girder bridges, system reliability is significantly different from element reliability. And thus it provides a more precise measure for the system safety, redundancy and capacity rating of existing steel box-girder bridges.

The equivalent system reliability-based capacity rating proposed in the paper can be effectively used in practice for the rating of deteriorated or damaged bridges to pick up reserve system-safety or strength for the optimal decisions in maintenance and rehabilitation.

In the case of composite steel box-girder bridges, the interactive failure limit state provides more critical element reliability than bending strength limit state.

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