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Reliability analysis on bridge piers subjected to seismic load

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ABSTRACT: As known that in multi-span continuous bridges, the failure of one member such as one pier in the bridges does not necessarily mean the failure(collapse) of the bridge system. To make the design of these bridges be more rational, the bridge piers should be designed not only as the independent structures but also as one structural members of the bridge system. To do that it is necessary to know what degree of reliabilities are provided on the bridge piers and the bridge system by the present design specifications. In this paper, reliabilities of the bridge piers and multi-span continuous bridge system under seismic load are determined and the problem of the present design specifications are discussed.

1 INTRODUCTION

In metropolitan highway bridge construction, there are recently many attempts to use multi-span continuous bridges instead of multi simple span bridges. For this reason, the design of these bridge piers is significant task. As known that in multi-span continuous bridges, which are redundant structures, the failure of one member such as one pier in the bridges does not necessarily mean the failure(collapse) of the bridge system. However, in the present design specifications of highway bridges(Japan Road Association, 1990), the bridge piers and allowable stresses used in their design are still designed and determined by the consideration of the safety of the bridge piers only. To make the design of multi-span continuous bridges be more rational, the bridge piers should be considered not only as the independent structures but also as the structural members in the bridge system.

To know what degree of reliabilities are provided on the bridge piers and the bridge system by the present design specification, in this paper reliabilities of the bridge piers and multi-span continuous bridge system under seismic load which is one of significant loads in design of bridges are determined and the problems of the present design specifications are discussed. In the reliability analysis, multi-span continuous bridges usually used in Tokyo metropolitan area are selected as representative structures. Reliabilities of the bridge piers and the bridge systems considered on ultimate limit state in flexure are computed by extended level 2 reliability method and the method proposed by Murotsu, Y., et al. (1981), respectively. Seismic load is modeled by Borges-Castanheta (B-C) load model. Material strengths are assumed to be random variables but others material properties are deterministic.

2 TYPICAL STRUCTURES AND STOCHASTIC MODEL OF ACTUAL LOADS

2.1 Typical structures

In this paper, five, seven and nine spans of multi-span continuous bridges usually used in metropolitain area are selected for reliability analysis. The superstructure of these bridges are continuous box girder having span lengths of 40 to 60 metres supported by reinforced concrete rigid-frame piers with height of 12 metres. Figure 1 shows configuration of multi-span continuous bridges in case of the five span type. Geometrical dimensions of each models are assumed as shown in Table 1. The cross sectional design of these model are designed by seismic load, which the material parameters and design criteria are shown in Table 2. All piers are assumed to have constant cross sections.

2.2 Stochastic model of actual loads

As shown in the work of Wen, Y.K. and Chen, H-C. (1989), it is generally recognized that failure of structural systems may be occurred by a progressive failures of members over a long period of time than sudden failure of all members at one time. And it

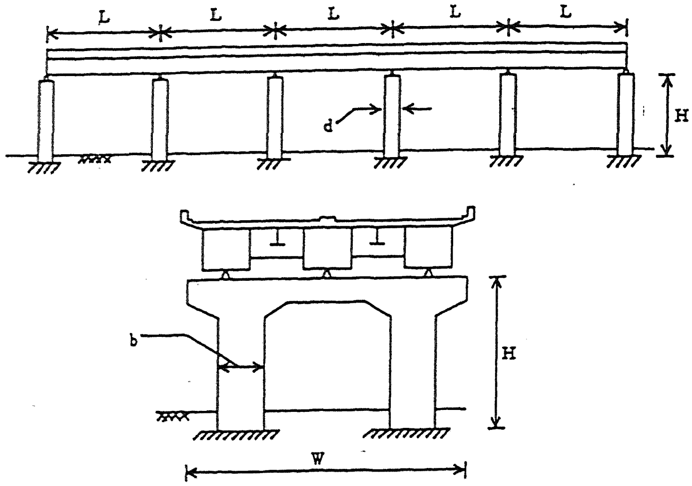

Figure 1 Configuration of five-span continuous bridge

Table 1 Geometrical dimensions of the models

Model No.	No. of Span	Span Length L	Pier Height H	Pier Width W	Column Width b	Column depth d
1		40.0	12.0	19.0	2.70	2.70
2	5	50.0	12.0	19.0	2.80	2.80
3		60.0	12.0	19.0	2.90	2.90
4		40.0	12.0	19.0	3.10	3.10
5	7	50.0	12.0	19.0	3.20	3.20
6		60.0	12.0	19.0	3.30	3.30
7		40.0	12.0	19.0	3.20	3.20
8	9	50.0	12.0	19.0	3.30	3.30
9		60.0	12.0	19.0	3.40	3.40

Unit: in metre

Table 2 Material Parameters and Design Criteria

Young's Modulus	
steel(SD30)	$E_s = 2.1\times10^6$ Kgf/cm^2
concrete	$E_c = 2.7\times10^5$ Kgf/cm^2
Linear Coefficient of Expansion	
(steel)	$\alpha = 1.2\times10^{-5}$/℃
Allowable Stress of Concrete	
	$f_{ca} = 80$ Kgf/cm^2
Allowable Stress of reinforcment	
	$f_{sa} = 1800$ Kgf/cm^2
Earthquake Load	$K_h = 0.3$

is necessary to consider the loads as time variant and their interaction with the system in the reliability analysis. For ease of the analysis,it is assumed that the failure of structural systems are occurred by the sudden failure of all-members at one time and the load process are modeled by a basic type of B-C load model(Christensen,P.T. and Baker, M.J. 1982).

Here,a 50 year design lifetime of a structure is assumed. The actual load models and their distributions functions are considered based on the followings: Dead load here, only the own weight of structures being invariant in time are considered; Seismic load is modeled as $K_h = S_a/g$,where S_a is linear acceleration response spectrum and g is the acceleration of gravity. The probability distribution of S_a is determined from earthquake data during 59 year(1926-1984) in Tokyo metropolitain area which their return period are more than 2 years(Japan Meteorological Agency,1926 to 1984). The attenuation formulas of acceleration response spectra for ground Grade 2 and the damping ratio of structures of 0.05 are used.

3 DETERMINATION OF STRUCTURAL RELIABILITY

3.1 Failure probability of bridge piers

To determine the failure probability of bridge pier,the multi-span continuous bridges are assumed as plane frame structures as shown in Figure 2. The failure

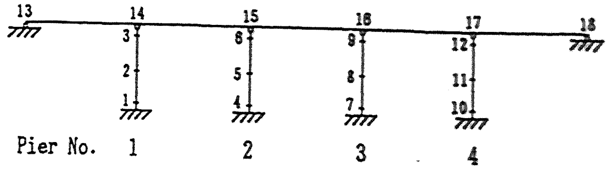

Figure 2 Analytical model of five span continuous bridge

probability of bridge piers are computed by using safety margins of column member ends which are generated by using a Matrix method as shown in the following equation.

$$M_i = R_i - S_i \qquad (1)$$

where R_i is the strength of column member end(ultimate flexural resistance of reinforced concrete pier) and S_i is the bending moment of the member end,calculated by using Matrix method and written in the form:

$$S_i = \sum_{j=1}^{3L} b_{ij} L_j \qquad (i=1,2,\ldots,2n) \qquad (2)$$

where L_j are the applied loads and b_{ij} are function of e.g. the moments of inertia of the member.

The failure criterion of the member end is given by

$$M_i \leqq 0 \qquad (3)$$

And the failure probability the member end is obtained by $P_f = \Phi(-\beta)$ where β is computed by the extended level 2 reliability method.

Ultimate flexural resistance of reinforced concrete piers subjected to combined bending and axial force are evaluated based on the equation recommended by the present design specifications. Herein, compressive strength f_c of concrete and yield strength f_y of reinforcement are considered as random variables and assumed to be normal distribution with mean of 288 and 3395 kgf/cm^2, respectively,and coefficient of variation of 0.2 and 0.05,respectively (Ozaka,Y. 1987). Mean and variance of the resistance are represented in Eq. 4 and 5, respectively.

$$\bar{M}_u = 0.68\bar{f}_c x b\left(\frac{h}{2}-0.4x\right) +0.0035A_s'E_s\left(\frac{x-d'}{x}\right)\left(\frac{h}{2}-d'\right)+A_s\bar{f}_y\left(\frac{h}{2}-d''\right) \qquad (4)$$

$$\sigma^2_{M_u} = \left[\left(0.34xbh-0.272bx^2\right)\right]^2\sigma^2_{fc} +\left[\left(\frac{A_s h}{2}-A_s d''\right)\right]^2\sigma^2_{fy} \qquad (5)$$

where M_u is ultimate resistant bending moment,A_s and A_s' are sectional area of tension and compression reinforcements, respectively, d' is distance from the extreme tension fiber to the centroid of tension reinforcements, d'' is distance from the extreme compression fiber to the centroid of compression reinforcements,b and h are width and height of member,respectively, E_s is modulus of elasticity of reinforcement, x is distance from the extreme compression fiber of the member to the neutral axis.

3.2 Failure probability of structural system

The computation of structural system reliability is a complex task,since it is necessary to enumerate all the failure modes as shown in the work of Shiraki,W.,et al. (1990). For small structural systems it may be possible to enumerate all failure modes,but for large structural systems it is impractical. In recent years,it is recommended that it is sufficient to consider only the so-called dominant failure modes in the computation of system reliability.

In this paper,the method presented by Murotsu,et al.(1981) is used. In this method the dominant failure modes are searched by a branch-and-bound method.

To identifying dominant failure modes, here the bridges are assumed as plane frame structures and the following assumption are used:

a) Structural members are uniform and homogeneous and external loads are applied to the joints of members.

b) Members are assumed to fail when the applied bending moments reach their fully plastic moments and critical sections where plastic hinges may form are the joints of members and the places at which the external loads are applied.

c) The behaviours of members are assumed to be perfectly elasto-plastic. Here,the structural failure is defined as formation of a mechanism in the structure. The failure modes and their safety margins are generated by using a Matrix method.

Here the short descriptions to identify dominant failure modes are given below.

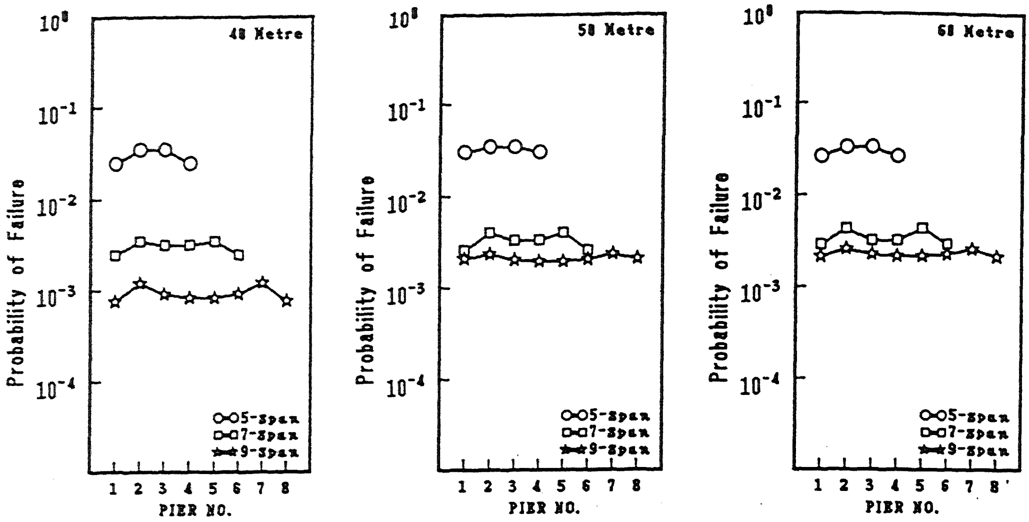

Figure 3 Failure probability of each pier ends

1. Failure probability of all member ends are computed as the same method as presented in subsection 3.1 and the member end first to fail is determined.

2. After any member ends have failed,the internal forces are redistributed to the member ends in survival (that means their stiffness matrices are replaced by the reduced ones and their residual strengths are applied to the nodes as artificial nodal forces). Then stress analysis of the structure is carried out once again. Then the failure probability of the member end in survival and the member end next to fail is determined again. The procedure above repeat until a mechanism is formed or until a specified number of members have failed. Formation of a mechanism here is determined by investigating the singularity of the total structure stiffness matrix.

3. Again,repeat the procedure above until all dominant failure modes have been found. An algorithm of searching for the dominant failure modes are carried out by a branch-and-bound method.

After,all of the dominant failure modes are obtained,the estimation of the failure probability of structural system is carried out.

4 NUMERICAL RESULTS

In this section,the reliability of bridge piers designed by seismic load are carried out.

Figure 3 shows the failure probability at each pier ends of each bridge models. It is found that the failure probabilities are varied from order 10^{-3} to 10^{-2}, which the mean value of failure probabilities of five span,seven span and nine span bridge models are 2.21×10^{-2},3.76×10^{-3} and 1.25×10^{-3},respectively. These results show that the failure probabilities are decreased when number of spans are increased.

To compare the failure probabilities of bridge piers with that of bridge systems, here the maximum failure probability of the pier ends of each bridge models are used and defined as the failure probability of member,which are obtained as the following. For bridge models No. 1,2 and 3,the failure probabilities of member are 2.74×10^{-2}, 2.62×10^{-2} and 2.46×10^{-2},respectively. For bridge models No. 4,5 and 6,the failure probabilities of member are 2.64×10^{-3}, 3.10×10^{-3} and 2.49×10^{-3},respectively. For bridge models No. 7, 8 and 9,the failure probabilities of member are 1.27×10^{-3}, 1.32×10^{-3} and 2.68×10^{-3},respectively.

Figure 4 shows the failure probabilities of member(bridge piers) and structural systems(bridge system). From this figure,it is found that the failure probability of structural systems are smaller than that of members. For bridge models No. 1,2 and 3,the failure probabilities of structural systems are 4.43×10^{-5}, 6.17×10^{-5} and 5.09×10^{-5}, respectively, which are decreased from that of member with order about 10^{-2} in these models. For bridge models No. 4,5 and 6,the failure probabilities of structural system are 2.98×10^{-11}, 8.82×10^{-11} and 2.36×10^{-11}, respectively, which are decreased from that of member with order about 10^{-7} in these models. For bridge models No. 7, 8 and 9,the failure probabilities of structural system are 1.86×10^{-15},2.46×10^{-15} and 9.41×10^{-13}, respectively, which are decreased from that

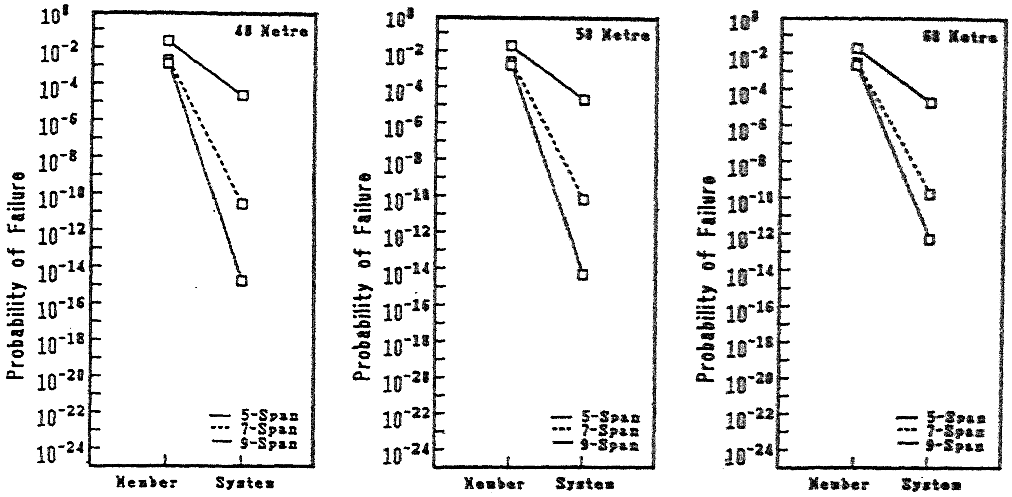

Figure 4 Failure probability of member and structural system

of member with order about 10^{-11}, 10^{-11} and 10^{-9}, respectively.

The above results show that the failure probabity of structural system are also decreased when number of spans are increased.

In the reliability theory of structural design, the target failure probability of member and structural system are recommended to have with order 10^{-1} to 10^{-3} and 10^{-5} to 10^{-7}, respectively. From these values, it can be said that the present design specification give an appropriate safety design to the design of bridge piers. However, if the target failure probability of structural system are considered, the present specifications give a large safety level to these continuous bridges, especially, the bridge which their number of spans are seven span or more.

Furthermore, from this study it is found that multi-span continuous bridges have great resistance to the seismic load and since the occurence of seismic load and failure probability of bridge systems subjected to seismic load are low, the safety factor used in the design of multi-span bridges can be decreased to the smaller value.

5 CONCLUSIONS

In this paper, the reliability analysis of bridge piers and bridge system subjected to seismic loads are presented. From this analysis, the following results are obtained.

1. The failure probability of bridge systems are smaller than that of bridge piers and the failure probabities of them are decreased when number of spans are increased. In general, this decrease are depended on the resistances of each piers and the redundancy of the bridge system.
2. The present design specification give an appropriate safety level to the design of bridge piers but large safety level to the bridge systems, especially, the continuous bridges which number of spans are seven span or more.
3. To make the design of multi-span continuous bridges be more rational, the safety factor used in the design of these bridges should be decreased to the smaller value.

However, since the consideration of only flexure limit state and actual loads are modeled by basic type of B-C load model, the reliability of bridge piers and bridge systems may be overestimated. In order to obtain a more correct results, it is required to analyze reliability of structures when a combined load effect of bending moment and an axial forces are applied and use a more correct load models, statistical data of actual loads.

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