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DEVELOPMENT OF SEISMIC DAMAGE EVALUATION SYSTEM FOR BRIDGE STRUCTURES BY USING DAMAGE TRANSITION MODEL

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SUMMARY

The Great Hanshin Earthquake had affected seriously on many highway bridges in Hanshin area. From a lot of investigations about the failure mechanisms on the highway bridges during strong earthquake, it was found that the consideration as a highway bridge system which consists of many structural elements such as piles, footings, piers, bearings, restrainers, super structures, etc. is very important to improve the practical design procedure. In this paper, an evaluation method for multiple damage states of bridge structural system due to strong earthquake is proposed. Then, the bridge structures were divided into each structural element from a systematic point of view, and these elements are interacted each other. Therefore, probability of multiple damage states of structural elements are evaluated by Marcov-chain model based on a damage transition probability matrix which can include damage interaction between the elements. The probability of multi-damage-states for the bridges with countermeasures against earthquakes such as strengthening work for pier, base isolation and fuse type bearing is calculated, and improvement in earthquake resistance of these bridges was estimated quantitatively.

INTRODUCTION

The falling down and collapse of reinforced concrete (RC) piers of elevated highway structures caused by the Hyogoken Nanbu Earthquake of 1995, also known as the Great Hanshin Earthquake, had a great impact on the subsequent rehabilitation efforts. Because many of the damaged structures were arterial roads constituting an important part of the land transportation network in Japan, the fallen or collapsed bridges severed road transportation routes and temporarily paralyzed goods distribution. The resultant economic losses were immeasurable. In view of the major damage and losses caused by the earthquake, work is now under way to revise the seismic design code [JRA 1996] applicable to the design of bridge structures from various viewpoints. The concept of the code, however, is still based on the design philosophy of ensuring the required earthquake resistance of the entire structural system by separately checking if individual components such as superstructure, substructure, bearings, and foundation satisfy strength and deformation capacity requirements. This is thought to be due to the lack of an established method for evaluating a bridge structure as a whole to ensure its earthquake resistance. If such a method can be established, it will be possible to predict, with some accuracy, functional losses of bridges in the event of greater-than-expected earthquake loading.

On the basis of this notion, the authors, thinking of a bridge as a structural system composed of a superstructure, bearings, restrainers, and a substructure, have been working on the modeling, by use of a damage transition probability matrix, of the mechanism by which the bridge components are damaged through their interactions under earthquake loading [Kaneyoshi *et al*. 1999]. The probabilities of damage states that can be calculated by use of the damage transition probability matrix can be expected to be useful for various purposes including the selection of seismic retrofit methods based on safety comparison or evaluation, prioritization of retrofit methods, and optimum design that takes incidental costs into consideration.

In this study, nonlinear dynamic analyses of the sections of the elevated Hanshin Expressway Kobe Route No. 3 (R-3) that were damaged by the Hyogoken Nanbu Earthquake are performed, and first-passage problems in random oscillation theory are applied to various response values obtained from the analyses. Then, a damage

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transition probability matrix considering interactions between damaged structural elements is constructed to express changes in damage state with a damage transition model. Finally, a prototype system for evaluating seismic damage by modeling a retrofitted bridge by the above technique and comparing damage states of the bridge and its model is developed (Figure 1).

DAMAGE TRANSITION OF THE ELEMENTS OF A BRIDGE STRUCTURAL SYSTEM

The seismic damage evaluation system expresses the state of damage to a bridge structure as transition in the state of damage to its structural elements and performs modeling on the assumption that transition in the state of damage to the structural elements follows a Markov-chain model. This section outlines how damage transition occurs.

Basic Model **[Ang and Tang 1984]**

The basic model is expressed with a state row vector, *S(t),* composed of the probability of each structural element's being in a particular state of damage (probability of damage state), as follows:

$$S(t)=\{s_1(t),s_2(t),s_3(t),\cdots,s_i(t),\cdots,s_n(t)\}$$

$$\sum_{i=1}^{n} s_i(t)=1.0 \qquad (1)$$

where $si(t)$: the probability of damage of state i at time t (i=1~n).

The initial value $S(0)$ of the state vector expressed by Eq. (1) is a deterministic vector with the probability of being in the initial state of 1.0 and the probability of being in any other state of 0.0. States are ranked by defining damage levels (threshold values) a, b and c ($a>b>c$) corresponding to four degrees of damage ($A>B>C>D$) suffered by individual members during an earthquake. State changes are assumed to be a Markov process with simple transitions and are expressed by using a state transition probability matrix, $P(t)$. It is assumed that transitions occur in proper sequence and do not skip ranks, such as jumping from D to B. The concept of this damage transition is illustrated in Figure 2. The damage transition probability matrix $P(t)$ is expressed as

$$P(t)=\begin{bmatrix} p_{AA}(t) & p_{BA}(t) & 0 & 0 \\ 0 & p_{BB}(t) & p_{CB}(t) & 0 \\ 0 & 0 & p_{CC}(t) & p_{DC}(t) \\ 0 & 0 & 0 & p_{DD}(t) \end{bmatrix} \qquad (2)$$

where $pij(t)$ is the probability of the transition from state i to state j in a unit of time at time t.

Let $S(t)$ represent a state row vector at time t, and $P(t)$, a damage transition probability matrix. The state row vector $S(t+dt)$ the unit of time dt later can be calculated from the equation

$$S(t+dt)^T = P(t)\times S(t)^T \qquad (3)$$

where T is matrix transposition.

Let T_0 represent the duration of state transition, and dt, a unit of time in transition. The number of transitions, then, is $n=T_0/dt$.

Constructing a Damage Transition Probability Matrix

To model the damage transition process, the seismic damage evaluation system calculates the probability of first-passage failure by regarding a response wave obtained from nonlinear dynamic analysis as a normal random process and applies the first-passage problem in the random vibration theory to structural elements. The system also calculates a damage transition probability matrix expressing changes over time in the probability of state of different structural elements. The sections that follow describe the procedure.

Calculating the probability of first-passage failure [Kitamura and Kaneyoshi 1979]

A response wave $x(t)$ obtained from a nonlinear dynamic analysis is treated as a normal random process with amplitude unsteadiness, and a structural element is taken as having been damaged when it has passed level $x(t)$ for the first time. The unsteady random process corresponding to the response wave is expressed as

$$x(t)=\sqrt{\varphi(t)}\cdot y(t) \tag{4}$$

where $y(t)$ is a normal steady random process with a mean value of 0.0 and a standard deviation of 1.0, and $\sqrt{\varphi(t)}$ is a determinate function of exponential type expressed as

$$\sqrt{\varphi(t)}=\left(\exp(-a't)-\exp(-b't)\right)\cdot c' \qquad \text{where } a', b', \text{ and } c' \text{ are constants } (0<a'<b') \tag{5}$$

If it is assumed that the phenomenon of the random process $x(t)$ expressed by Eq. (4) passing a given particular level is rare and that the number of occurrences of exceedance can be modeled by the Poisson process, the probability of first-passage failure for two side levels (a, $-a$) can be calculated from the following equation:

$$Pa(t)=1-\exp\left\{-2\int_0^T p_+(a,t)dt\right\} \tag{6}$$

where $p_+(a,t)$ is the probability that the random process $x(t)$ exceeds level a at a positive gradient in a unit of time at time t. Similar calculations are made for levels b and c.

Constructing a damage transition probability matrix

The probability of each state of damage for the probabilities of first-passage failure calculated in the preceding section is calculated. The probability of first-passage failure for level a is defined as the probability of damage state A, or $PA(t)$. The probability of being damaged at the first passage of level b but never passing level a is defined as the probability of damage state B, or $PB(t)$. The probability of being damaged at the first passage of level c but never passing level b is defined as the probability of damage state C, or $PC(t)$. The probability of never passing level c is defined as the probability of damage state D, or $PD(t)$. Thus, the different states of damage are expresses as follows:

$$\begin{aligned} PA(t) &= Pa(t) \\ PB(t) &= Pb(t) - Pa(t) \\ PC(t) &= Pc(t) - Pb(t) \\ PD(t) &= 1.0 - Pc(t) \end{aligned} \tag{7}$$

Next, the probability of damage transition during the period between time t and time $t+\Delta t$, that is, the elements of which the damage transition probability matrix is composed are defined as follows:

Probability of staying in state A: $P_{AA}(t) = 1.0$ (8)

Probability of transition from state B to state A: $P_{BA}(t+\Delta t)=\{PA(t+\Delta t)-PA(t)\}/PB(t)$ (9)

Probability of staying in state B: $P_{BB}(t+\Delta t) = 1.0 - P_{BA}(t+\Delta t)$ (10)

Probability of transition from state C to state B: $P_{CB}(t+\Delta t) = 1.0 - P_{CC}(t+\Delta t)$ (11)

Probability of staying in state C: $P_{CC}(t+\Delta t) = [PC(t+\Delta t)-\{PD(t)-PD(t+\Delta t)\}]/PC(t)$ (12)

Probability of transition from state *D* to state *C*: $P_{DC}(t+\Delta t) = \{PD(t) - PD(t+\Delta t)\}/PD(t)$ (13)

Probability of staying in state *D*: $P_{DD}(t+\Delta t) = 1.0 - P_{DC}(t+\Delta t)$ (14)

where 0.0 $P_{DD}, P_{DC}, P_{CC}, P_{CB}, P_{BB}, P_{BA}, P_{AA}$ 1.0

Equs. (8) to (14) are used to construct damage transition probability matrices for different states of damage.

Nonlinearity of Damage Transition

In the seismic damage evaluation system, the state of all structural elements before an earthquake is assumed to be *D*, and the initial state *S*(0) is expressed as

$$S(0) = [0 \quad 0 \quad 0 \quad 1] \tag{15}$$

The progress of bridge damage during an earthquake is nonlinear. To express this progress of damage, damage transition in a unit of time is assumed to follow a uniform Markov-chain model, and such changes in state are expressed, using multiple damage transition probability matrices, as follows:

$$S(n) = S(n-1)P(n-1,n) = S(n-2)S(n-2,n-1)P(n-1,n) = \cdots = S(0)\prod_{k=0}^{n-1} P(k,k+1) \tag{16}$$

DAMAGE TRANSITION IN BRIDGE STRUCTURAL SYSTEM

Interaction of Structural Element Damage

A bridge is a structural system composed of various elements, and the structural elements interact in various ways. Serious functional problems due to earthquake damage often occurs when bearings, restrainers, or piers have been damaged. In the seismic damage evaluation system, therefore, structural elements considered in modeling are limited to bearings, girder joint devices, seat length, and piers (Figure 3). In considering pier (RC pier) damage, attention is paid to flexural damage to the column base, and the girder joint devices and seat length were considered only in the longitudinal (bridge axis) direction.

Representation of Damage Transition

The seismic damage evaluation system models damage transition taking into consideration the mutual effects between bridge structural elements during an earthquake. Those effects are expressed as interactions between elements. Interaction between elements is expressed by modifying the damage transition probability matrix for the element being influenced when the state of the influencing element has exceeded a certain value. Therefore, cases where elements are influenced so as to increase damage (Eqs. (17) and (18)) and cases where elements are influenced so as to decrease damage (Eqs. (19) and (20)) are considered. Constants α to κ expressing the degree of interaction (which ranges from 0.0 to 1.0 and which remains constant in the transition process) are used, and interaction is expressed by modifying the damage transition probability matrix.

Case where damage increases

$$\begin{bmatrix} P_{AA}(t,t+\Delta t) & P_{BA}(t,t+\Delta t)+\gamma\times P_{BB}(t,t+\Delta t) & 0 & 0 \\ 0 & P_{BB}(t,t+\Delta t)-\gamma\times P_{BB}(t,t+\Delta t) & P_{CB}(t,t+\Delta t)+\beta\times P_{CC}(t,t+\Delta t) & 0 \\ 0 & 0 & P_{CC}(t,t+\Delta t)-\beta\times P_{CC}(t,t+\Delta t) & P_{DC}(t,t+\Delta t)+\alpha\times P_{DD}(t,t+\Delta t) \\ 0 & 0 & 0 & P_{DD}(t,t+\Delta t)-\alpha\times P_{DD}(t,t+\Delta t) \end{bmatrix} \tag{17}$$

$$\begin{bmatrix} P_{AA}(t+\Delta t) & P_{BA}(t+\Delta t)+\varepsilon\times P_{BB}(t+\Delta t) & 0 \\ 0 & P_{BB}(t+\Delta t)-\varepsilon\times P_{BB}(t+\Delta t) & P_{CB}(t+\Delta t)+\delta\times P_{CC}(t+\Delta t) \\ 0 & 0 & P_{BB}(t+\Delta t)-\delta\times P_{CC}(t+\Delta t) \end{bmatrix} \tag{18}$$

Case where damage decreases

$$\begin{bmatrix} P_{AA}(t,t+\Delta t) & P_{BA}(t,t+\Delta t)-\theta\times P_{BA}(t,t+\Delta t) & 0 & 0 \\ 0 & P_{BB}(t,t+\Delta t)+\theta\times P_{BA}(t,t+\Delta t) & P_{CB}(t,t+\Delta t)-\eta\times P_{CB}(t,t+\Delta t) & 0 \\ 0 & 0 & P_{CC}(t,t+\Delta t)+\eta\times P_{CB}(t,t+\Delta t) & P_{DC}(t,t+\Delta t)-\zeta\times P_{DC}(t,t+\Delta t) \\ 0 & 0 & 0 & P_{DD}(t,t+\Delta t)+\zeta\times P_{DC}(t,t+\Delta t) \end{bmatrix} \tag{19}$$

$$\begin{bmatrix} P_{AA}(t+\Delta t) & P_{BA}(t+\Delta t)-\kappa\times P_{BA}(t+\Delta t) & 0 \\ 0 & P_{BB}(t+\Delta t)+\kappa\times P_{BA}(t+\Delta t) & P_{CB}(t+\Delta t)-\tau\times P_{CB}(t+\Delta t) \\ 0 & 0 & P_{BB}(t+\Delta t)+\tau\times P_{CB}(t+\Delta t) \end{bmatrix} \tag{20}$$

PRACTICAL APPLICATION

Target Structure and Conditions for Analysis [Kaneyoshi *et al.* 1999]

Target structure

The structure subjected to the nonlinear dynamic analysis is a representative RC bridge pier whose lowest part failed in bending during the Hyogoken Nanbu Earthquake. The pier was modeled as a cantilever type, T-shaped, single circular column pier as shown in Figure 4. Data on this RC pier are shown in Table 1.

Conditions for analysis

The bridge structure was subjected to an elastoplastic seismic response analysis carried out by the direct integration method using the Newmark's beta method (β =0.25, average acceleration method). The time step used is 0.002 s. Damping of all structural elements was assumed to be proportional to rigidity. By referring to the values given for reference in *Standard Specification for Highways* in Japan, the damping factor of 2% was adopted for the pier structure, and 20% for the foundation structure [JRA 1996].

As shown in Figure 4, the analytical model is a multiple-mass skeleton model with pier beams and footing modeled as rigid elements. The superstructure, pier beams, and footing were treated as a concentrated mass model, and the pier column as a distributed mass model. The bearings were modeled as a double-node system, and the nodes were interconnected by rigid springs. The pile foundation and the soil were modeled as equivalent linear springs by referring to *Standard Specification for Highways* in Japan. For nonlinearity of the column, a trilinear model shown in Figure 5, taken from *Reference Data for Application of "Specifications Concerning Restoration of Bridges Damaged by Hyogoken Nanbu Earthquake"(Draft)* [JRA 1995], was employed, and the Takeda's model considering cracking in the concrete and decreases in rigidity due to the yielding of reinforcing bars was used.

The ground motion recorded at the Kobe Marine Observatory, a representative strong motion record obtained during the Hyogoken Nanbu Earthquake, was used as the input strong motion. The excitation directions were the transverse direction (input ground motion: NS component, maximum acceleration: 818 gals) and the longitudinal direction (input ground motion: EW component, maximum acceleration: 617 gals).

Defining Damage States

In order to calculate the probability of first-passage failure corresponding to the response values obtained from the dynamic analysis, it is necessary to define the boundary levels described in Section 2.1. In the seismic damage evaluation system, for the response values of horizontal displacement of the pier base relative to the pier top, $B \longrightarrow A$ displacement was defined as ultimate displacement (δ_u), $C \longrightarrow B$ displacement as 3 times yield displacement ($3\times\delta_y$), and $D \longrightarrow C$ displacement as yield displacement (δ_y). For the response values of bearing reaction, the $B \longrightarrow A$ reaction was defined as the yield strength of the bearing, and the $C \longrightarrow B$ reaction as the allowable strength of the bearing.

Conditions for Interaction among Structural Elements

For the seismic damage evaluation system, the damage transition as shown in Figure 6 was assumed taking into consideration interaction action among bridge structural elements. Because bridge behavior during an earthquake varies depending on the direction of movement, interaction between the structural elements was considered, on the basis of the states of bridge damage in the longitudinal and transverse directions, as described below.

Interaction associated with RC pier column damage

If the overall deformation of the pier structure has increased because of column base damage, damage to the girder joint devices progresses as relative displacement in the longitudinal direction between adjoining superstructure elements increases. Interaction with the bearings is ignored because the response values of the bearings obtained in the dynamic analysis include the effects of pier damage. Interaction associated with pier column damage is expressed by modifying the damage transition probability matrix for the girder joint devices by use of Eq. (17) when the element *PA* of the damage state probability for the pier has exceeded 0.5. The parameters for matrix modification used in Eq. (17) are all 0.005.

Interaction associated with bearing damage

If a bearing member has been damaged so as to allow deformation, inertial forces from the superstructure acting on the pier column decreases and the progress of pier column damage is slowed down. This interaction is expressed by modifying the damage transition probability matrix for the pier by use of Eq. (19) when the element *PA* of the bearing damage probability has exceeded 0.5. The parameters used in Eq. (19) for matrix modification were ζ =0, η =0.772, and θ =1. For the purposes of this study, the parameters were set so as to be compatible with the damage state probabilities calculated by applying the random vibration theory to the response values obtained from a dynamic analysis for the bridge axis direction considering bearing failure. In the longitudinal direction, if a bearing-superstructure connection (set bolts, etc.) has been damaged, relative displacement between adjoining superstructure elements becomes large and the girder joint devices are damaged. If a bearing-pier connection (anchor bolts, seat concrete, etc.) has been damaged, relative displacement between the superstructure and the substructure becomes large so that seat length is decreased. This interaction is expressed by modifying the damage transition probability matrices for the girder joint devices and seat length by use of Eq. (17) when the element *PA* of the damage state probability for bearings has exceeded 0.5. The parameters used for matrix modification and for seat length were 0.01 and 0.005, respectively.

Interaction associated with girder joint device damage

In cases where girder joint devices are damaged, usually the bearings are already in an ultimate state. As the girder joint devices fail, relative displacement not only between adjoining superstructure elements but also between the superstructure and the substructure increases so that seat length is decreased (damaged). This interaction is expressed by modifying the damage transition probability matrix for seat length by use of Eq. (17) when the element *PA* of the damage state probability for the girder joint devices has exceeded 0.5. The parameters used in Eq. (17) for matrix modification are all 0.01.

Interaction Conditions in Cases where Seismic Retrofit Measures are taken

Various seismic retrofit measures have been devised and put to practical use in order to improve the seismic performance of bridges. The seismic damage evaluation system was applied to the strengthening of piers against bending, base isolation, and the introduction of fuse-type bearings to evaluate the effects of these seismic retrofit measures.

Longitudinal direction

(1) Use of pier strengthening work: Pier strengthening is a method of increasing the flexural load-bearing capacity and deformation capacity of RC pier columns by increasing their rigidity. The progress of pier column damage, therefore, is reduced even if the pier columns are acted upon by earthquake loads. This damage-reducing effect is expressed by modifying the damage transition probability matrix at each transition step of the bridge pier by use of Eq. (19). It is expected that while column damage will be reduced, inertial forces exerted by the superstructure on the bearings, which connect the superstructure and the substructure, will increase. This effect, therefore, is expressed by modifying the damage transition probability matrix at each transition step of the bearings by use of Eq. (18).

(2) Use of base isolation bearings: Base isolation bearings are used to reduce inertial forces exerted by the superstructure on the substructure. When applied to an actual bridge, this method is expected to slow down the progress of pier column damage as well as strengthening the pier columns. This damage-reducing effect,

therefore, is expressed with Eq. (19). It is assumed that base isolation bearings will not be damaged to the extent of reaching an ultimate state.

Transverse direction

(1) Use of pier strengthening: As in the longitudinal direction, the effect of RC pier strengthening is expressed by modifying the damage transition probability matrices for the pier and the bearings by use of Eqs. (18) and (19).

(2) Introducing the fuse effect: One approach currently being studied is the introduction of a "fuse" concept, which aims to reduce inertial forces exerted by the superstructure on the substructure by designing bearings so as to fail at a load level lower than the conventional strength standard. The fuse effect, which reduces the progress of damage, was programmed into the seismic damage evaluation system on the assumption that this effect occurs to so as improve the seismic performance of the bridge in the transverse direction after the bearings have been damaged to a certain degree. This effect is expressed, in the damage transition process of the damage transition model, by modifying the damage transition probability matrix for the pier at each step by use of Eq. (19) and the damage transition probability matrix for the bearings by use of Eq. (18) when the element *PA* of the damage state probability for the bearings has exceeded 0.5.

Evaluation of Seismic Performance

On the basis of the interactions considered in the previous sections, the seismic damage evaluation system was applied to a bridge model (with seismic retrofit, without seismic retrofit). In all cases, matrices were constructed by limiting the time in which damage transition behavior is evaluated to 4 to 16 s. The time step used was Δt=0.12 s and the number of transitions was 100. The elements of the damage transition probability matrix at each time step (Δt) were calculated from Eqs. (8) to (14), and a damage transition model was constructed according to the damage transition matrices thus obtained.

Evaluation of non-seismic-retrofit model

Figures 7 and 8 show damage state probabilities calculated using the non-seismic-retrofit model. The screen displays shown in Figures 7 and 8 are the system's output screens showing the changing state of bridge damage over time. The output screens of the system display a state that maximizes the final damage state probability for each structural element as a representative state of damage so that changes in the state of the bridge structure over time can be checked easily. The output screens are also designed to make it easy to check damage transitions of different elements by visualizing the damage transition status. The status information shown on the screens of Figs. 7 and 8 indicates that in the longitudinal direction, the damage to the bearings is greater than the damage to the pier column, and that in the transverse direction, higher probabilities of damage mean greater damage to the pier column than to the bearings although the visualized representations are similar.

Evaluation of seismic retrofit model

Parameters necessary for matrix modification were extracted from the results of the dynamic analysis of a seismically retrofitted bridge model. Examples of parameters (parameters for pier strengthening) thus obtained are shown in Tables 2, 3, 4, and 5. Results obtained by applying these parameters to different seismic retrofit measures are also shown by direction.

(1) Longitudinal direction: Figures 9 to 11 show changes over time in damage state probability in the cases where different seismic retrofit measures are taken for the damage transition model for the longitudinal direction. Comparison with Figure 7 with respect to changes in the probability of different states due to pier strengthening reveals that the probability of state *A* for the pier has become zero and the probability of state *B* has increased considerably. This indicates that pier strengthening dramatically improves the seismic performance of the pier. For the bearings, the probability of state *A* has somewhat increased; because of this, the probabilities of states *B*, *C*, and *D* have decreased slightly for both the girder joint devices and seat length, and the probability of state *A* has risen. This means that pier strengthening resulted in a slight reduction in the seismic performance of the pier. Examination of changes in the probability of different states for the base isolation bearings reveals that the probability of damage state *A* for the pier has become zero. This indicates that the seismic performance of the pier has been improved considerably as in the case of pier strengthening. With respect to the girder joint devices and seat length, the initial damage states have remained unchanged because the probability of state *A* for the base isolated pier does not exceed 0.5 and because it is assumed for the purposes of the present study that the base isolation bearings do not fail. Examination of the changes in the probability of the different states in the cases

where pier strengthening and base isolation bearings are used in combination indicates that the probability of damage state *A* for the pier has become zero. This indicates that the seismic performance of the pier has been improved considerably. From comprehensive evaluation of the above results, it can be seen that although combined use of pier strengthening and base isolation is supposed to lead to the greatest improvement in seismic performance, the degree of improvement is not as great as that achieved in the case where base isolation alone is used. Of the three seismic retrofit measures applied, use of base isolation alone is the most reasonable method.

(2) Transverse direction: Figures 12 to 14 show changes over time in the probability of different damage states in the cases where different seismic retrofit measures are applied to the damage transition model for the transverse direction. Comparison with Figure 8 with respect to the changes in the probability of different states due to pier strengthening reveals that the probability of damage state *A* for the pier has become zero, indicating a considerable improvement in the seismic performance of the pier. As for the bearings, the probability of state *A* has risen slightly, and seismic performance has declined. Bearings with the fuse effect, which are designed to fail under a working load equal to $1/\sqrt{3}$ of the design strength of existing bearings and then exert bilinear restoring forces with a limit equal to the working load, were also applied to the damage transition model. As a result, the probability of damage state A for the pier decreased by about 0.2, and it can be seen that damage was reduced, though only slightly. As can be seen from Figure 13, the probability of damage state *A* for the fuse type bearings is close to 1.0, so that an ultimate state was reached in all cases. The damage-reducing effect in the case where seismic retrofit measures were used in combination was greater than in the cases where individual measures were used independently, but that effect was due mostly to the use of pier strengthening.

CONCLUSIONS

In this study, a bridge structure is considered to be a structural system composed of a superstructure, bearings, substructure, and joint devices, and a method for modeling the progress of damage over time has been presented. In this connection, a dynamic analysis of a viaduct structure of the Hanshin Expressway, which was damaged by the Hyogoken Nanbu Earthquake was performed. By applying the first-passage problem in the random vibration theory to the response values obtained through the analysis, damage transition probability matrices were constructed and the progress of bridge damage over time was modeled. This damage transition model was used to develop a prototype system for evaluating the effectiveness of different seismic retrofit measures applied to a bridge. The main results obtained from this study are summarized as follows:

(1) Nonlinear damage transition of bridge structural elements was expressed by assuming that the progress of damage to bridge elements follows a Markov-chain model and by modifying the damage transition probability matrix at each transition step.

(2) Introduction of parameters for matrix modification into the damage transition probability matrix has enabled expression of interaction among structural elements and evaluation of the effects of different seismic retrofit measures.

(3) Development of a program for visualizing damage transition over time has made it possible to easily check the transition of structural element damage in the behavior of the entire bridge structure during an earthquake. By comparing cases with and without seismic retrofits, the effects of different seismic retrofit measures on seismic performance can be evaluated.

(4) The damage process of structural elements has been expressed by using a damage transition model on the basis of overall bridge behavior during an earthquake. Thus, a basic structure of a system for evaluating the seismic performance of structures has been developed.

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