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Seismic Performance of Isolated Bridges Considering Long-term Deterioration of Isolators

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ABSTRACT: Mechanical properties of natural rubber seismic isolators are varied due to aging deterioration. It is needed that seismic performance of isolated bridges are maintained considering aging deterioration of isolators over their lifetime. In this study, seismic failure modes and seismic safety of isolated bridges were evaluated considering uncertainties in the material and mechanical properties and aging deterioration of isolators. It was shown that seismic safety of the isolated bridges is mainly controlled by the rupture strain of the isolator if the ultimate capacity ratio between the isolator and the column is low and that adequate capacity ratio is needed to enhance seismic safety and reparability of isolated bridges.

1. INTRODUCTION

Reinforced concrete bridge columns with seismic isolators subjected to the design ground motion are designed within limited nonlinear response to ensure that seismic energy is mainly dissipated at isolators. To realize this design concept, the yield strength of the isolator is set to be lower than that of the reinforced concrete column so that the isolator yields in advance under the design ground motion from view point of capacity design method (Park & Otsuka (1999), Jangid (2007) and Zhang & Huo (2009)). However, lateral force of the isolator can increase due to the post-elastic stiffness under more severe ground motion. This increase in the lateral force of the isolator can result in rupture of the isolator or large nonlinear response displacement of the column. Once isolators are ruptured, several months will be needed to repair permanently, since isolators are designed for each bridge and manufactured after receiving an order. Thus it is necessary to prevent rupture of isolators to enhance reparability of isolated bridges after seismic events. Uncertainties in evaluating the mechanical properties, especially rupture strain of isolators are inevitable. Furthermore, it is also needed to consider strain hardening of the isolator to evaluate seismic response in such a large shear strain range.

It is well known that mechanical properties of natural rubber seismic isolators are varied due to aging deterioration. Long-term deterioration characteristics of natural rubber bearings were reported based on accelerated thermal oxidation tests by Itoh & Gu (2009). Furthermore, decrease in rupture strain and increase in stiffness of isolators of actual bridges due to aging deterioration has been reported by Hayashi *et al.* (2014) and Shinohara & Hoshikuma (2015). It is important that seismic safety and reparability of isolated bridges with deteriorated isolators are maintained as well as those with sound isolators.

In this study, the effects of long-term deterioration of isolators on the seismic failure modes and seismic safety of isolated bridges will

Table 1: Dimensions of the target bridges.

		Bridge A	Bridge B	Bridge C	Bridge D
Superstructure	Mass (ton)	600			
Isolator (LRB)	Section (mm)	450	500	550	600
	Total thickness of rubber (mm)	80	100	120	140
	Diameter (mm) and number of lead core	75×4	75×4	75×4	75×4
Column	Section (mm)	2600×2400			
	Height (mm)	10000			
	Mass (ton)	260			
	Longitudinal reinforcement ratio (%)	1.41 %			
	Volumetric ratio of tie (%)	0.87 %			

Table 2: Mechanical properties of the isolator per column.

Bridge	Yield strength Q_{BY} (MN)	Yield stiffness K_{B1} (MN/m)	Strength at hardening initiation Q_{BH} (MN)	Equivalent stiffness K_{BEQ} (MN/m)
Bridge A	0.870	51.4	2.00	14.1
Bridge B	0.870	56.6	2.48	13.6
Bridge C	0.870	61.4	3.00	13.5
Bridge D	0.870	66.0	3.58	13.7

Table 3: Mechanical properties of the column.

Yield strength Q_{CY} (MN)	Yield displacement (mm)	Ultimate displacement δ_{ls3} (mm)
3.43	33.8	203

Table 4: Capacity ratios and equivalent natural periods.

Bridge	R_{QY}	R_{QU}	T_{EQ} (s)
Bridge A	0.25	1.73	1.66
Bridge B	0.25	2.11	1.68
Bridge C	0.25	2.53	1.69
Bridge D	0.25	3.00	1.68

be investigated based on dynamic response analysis and fragility analysis.

2. TARGET BRIDGES AND ANALYTICAL CONDITIONS

2.1. Target bridges and analytical model

It is an advantage of using LRB that property of LRB can be easily controlled by the diameter of lead core and dimensions of rubber, which is associated with capacity ratios R_{QY} by Zhang & Huo (2009) and R_{QU} by Matsuzaki *et al*. (2017), respectively.

$$R_{QY} = Q_{BY} / Q_{CY} \tag{1}$$

$$R_{QU} = Q_{BR} / Q_{CU} \tag{2}$$

where Q_{BY} is the yield strength of the isolator, Q_{CY} is the yield strength of the column, Q_{BR} is the rupture strength of the isolator and Q_{CU} is the ultimate strength of the column.

Target bridges are reinforced concrete columns with 5 square lead rubber bearings (LRB) at the top of a column on the stiff soil. 4 bridges were considered as shown in Table 1. Every target bridges were designed based on the design specifications of highway bridges by Japan Road Association (2012) and the manual on bearings for highway bridges by Japan Road Association (2004). It is noted that safety margins for the isolator are different among the target bridges controlled by Equations (1) and (2). Mechanical properties of the isolators and the reinforced concrete columns are shown in Tables 2 and 3, respectively. The values of R_{QY}, R_{QU} and

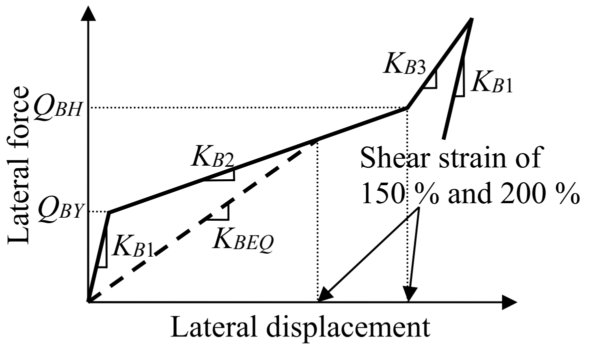


Figure 1: Lateral force-lateral displacement relationship of isolators.

the values in Tables 2-4 were calculated using nominal values in the design based on Equations (1)-(3).

$$T_{EQ} = 2\pi\sqrt{(M_U + M_C)(1/K_{BEQ} + 1/K_{CY})} \quad (3)$$

where M_U is the mass of superstructure, M_C is the mass of the column, K_{BEQ} is the equivalent stiffness of the isolator as shown in Figure 1 and K_{CY} is the yield stiffness of the column.

LRB was idealized based on a tri-linear model considering strain hardening of rubber as shown in Figure 1. In Figure 1, the ratio of K_{B1} to K_{B2} was set as 6.5:1 based on Japan Road Association (2004) and the ratio of K_{BEQ} to K_{B3} was set as 1:2.59 based on Adachi (2002). Skeleton and hysteresis of reinforced concrete columns were idealized based on bi-linear model and Takeda degrading stiffness model by Takeda *et al*. (1970), respectively. Thus the ultimate strength was idealized as same as the yield strength of the column. Dynamic response analysis was conducted by idealizing a reinforced concrete column with isolators as a 2 degree of freedom model. Rayleigh damping was assumed, in which the damping ratios of the column and the isolator were 2 % and 0 %, respectively.

2.2. Long-term deterioration characteristics of isolators

Long-term deterioration characteristics of isolators were modelled based on accelerated thermal oxidation tests by Itoh *et al*. (2006) and Itoh & Gu (2009).

Variations of mechanical properties of rubber due to aging deterioration are limited within the critical depth from the surface. This aging deterioration of surface rubber affects the mechanical properties as bearings. Itoh *et al*. (2006) proposed the following equation to predict the variation of shear stiffness of rubber bearings. K_{B1}, K_{B2} and K_{B3} in Figure 1 were varied according to the ratio obtained by Equation (4).

$$K_{BEQ} / K_{BEQ0} = 1 + k_s \Delta f_s \quad (4)$$

$$\Delta f_s = 0.066 t_{ref}^{0.515} \quad (5)$$

$$k_s = 2d^*(a + b - d^*) / 3ab \quad (6)$$

$$d^* = \alpha \cdot \exp(\beta / T) \quad (7)$$

where K_{BEQ0} is the initial equivalent shear stiffness, t_{ref} is the equivalent time in the accelerated thermal oxidation tests, a and b is the width of bearing, d^* is the critical depth, α=8.0×10^{-4} mm, β=3.3×10^3 K. T was set as 288.15 K (15 °C) in this study.

Real service time t is converted into t_{ref} based on Arrhenius methodology.

$$\ln(t_{ref} / t) = E_a / R(1/T_{ref} - 1/T) \quad (8)$$

where E_a is activation energy of the rubber and set as 9.94×10^{4}J/mol, R is gaseous constant (=8.31 J/(mol·K)).

It has been reported that decrease ratio of rupture strain is almost same as increase ratio of shear stiffness based on the loading tests of isolators used for actual bridges. Thus it was assumed that decrease ratio of rupture strain is same as increase ratio of shear stiffness in this study.

2.3. Uncertain factors and fragility analysis

Uncertainties in the material and mechanical properties of isolated bridges were included in the analysis. Uncertain factors considered in the analysis are listed in Table 5 with coefficients multiplied by nominal values or calculated values. Statistical values were based on Adachi

Table 5: Uncertain factors and coefficients multiplied by characteristic value.

Uncertain factor		Distribution	Characteristic value	Coefficient	
				Mean	C.O.V
Superstructure	Mass	Normal	600 ton	1.05	0.05
Isolator	Yield strength	Normal	Listed in Table 2	1.13	0.18
	Stiffness	Normal	Listed in Table 2	1.00	0.07
	Rupture strain	Normal	250 %	1.34	0.11
Column	Compressive strength of concrete	Normal	23.5 N/mm^2	1.20	0.10
	Section area of steel bar	Normal	Nominal value	0.97	0.01
	Yield strength of steel bar	Normal	295 N/mm^2	1.20	0.07
	Young's modulus of steel bar	Normal	2.06×10^5 N/mm^2	0.97	0.01
	Mass	Normal	260 ton	1.05	0.05
	Ultimate displacement	Normal	Calculated based on JRA (2012)	1.062	0.181

Table 6: Input ground motions.

Earthquake	Recording station
1995 Kobe	Inagawa (Hanshin Expressway), Kobe (JMA), Kobe University and Shin-Kobe (KEPCO)
2000 Tottoriken-Seibu	Niimi (EW, K-NET), Hakuta (KiK-net) and Hino (KiK-net)
2001 Geiyo	Yuki (EW, K-NET)
2004 Niigataken-Chuetsu	Ojiya (K-NET), Tookamachi (K-NET) and Nagaoka (KiK-net)
2007 Noto	Togi (K-NET) and Wajima (K-NET)
2008 Iwate-Miyagi	Ichinoseki-Nishi (KiK-net), Ichinoseki-Higashi (KiK-net), Naruko (K-NET) and Higashi-Naruse (KiK-net)
2016 Kumamoto	Ichinomiya (K-NET), Ohzu (K-NET), Oguni (EW, KiK-net), Kikuchi (NS, KiK-net), Takamori (EW, K-NET) and Yabe (NS, K-NET)

∗ Horizontal components of ground motions with SI of 30 cm/s or more were selected. Recording station with no direction means that both NS and EW components were selected.

(2002) and Public Works Research Institute (2013).

Fragility analysis was conducted based on Monte Carlo simulation considering the uncertainties listed in Table 5. Number of trials in Monte Carlo simulation was set as 80,000. In fragility analysis, limit states associated with the lateral displacement of isolators and columns were considered. Threshold values are rupture strain for isolators and ultimate displacement δ_{ls3} for columns based on Japan Road Association (2012). If the response displacement exceeds the ultimate displacement of the column in advance, it is considered that the column is damaged. On the other hand, if response shear strain exceeds the rupture strain of the isolator in advance, it is considered that the isolator is damaged. If the isolator or the column of the bridge is damaged, it is considered that the bridge system is damaged.

2.4. Input ground motions

Horizontal components of ground motions with SI of 30 cm/s or more recorded at stiff soil in Japan were selected as shown in Table 6. SI was

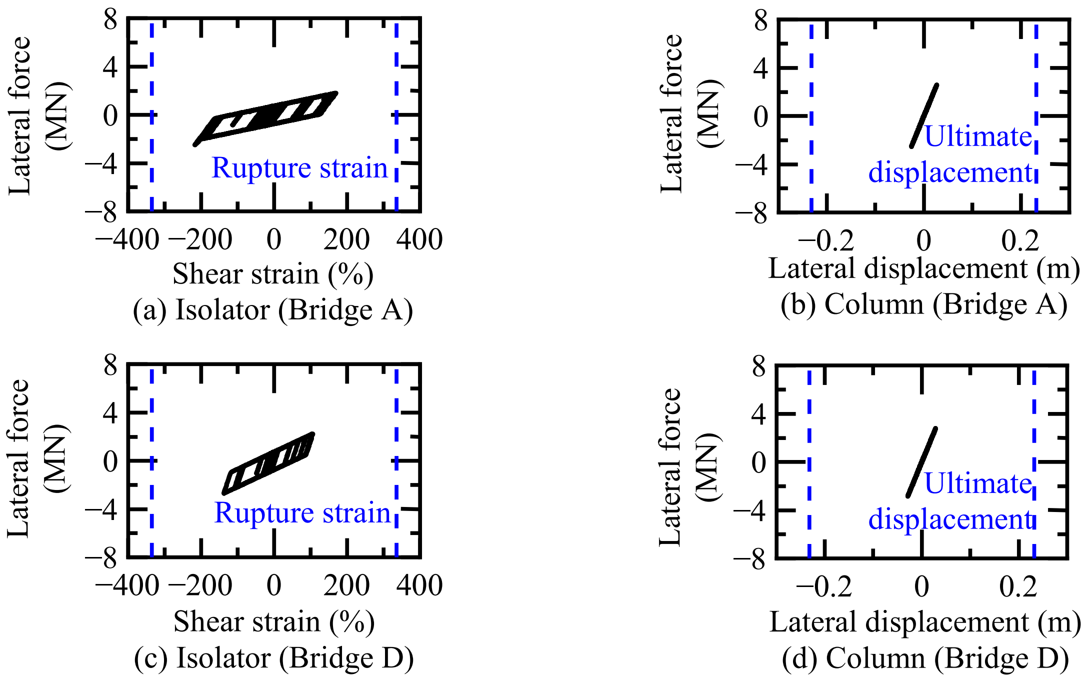


Figure 2: Response of isolated bridges subjected to NS component of JMA Kobe record (t=0 and SI is adjusted to 95 cm/s).

adopted as the intensity measure in the fragility analysis because SI has good agreement with the peak nonlinear response displacement of structures. As input ground motions in the fragility analysis, ground motions adjusted to the required SI by varying amplitude property were used without varying phase property.

The mean value of SI of the design ground motions (Level 2 and Type II on the stiff soil) by Japan Road Association (2012) is 95 cm/s. Thus ground motions with SI of 95 cm/s are treated as ground motions which have the same intensity with the design ground motions.

3. LONG-TERM SEISMIC PEFORMANCE OF ISOLATED BRIDGES CONSIDERING DETERIORATION OF ISOLATORS

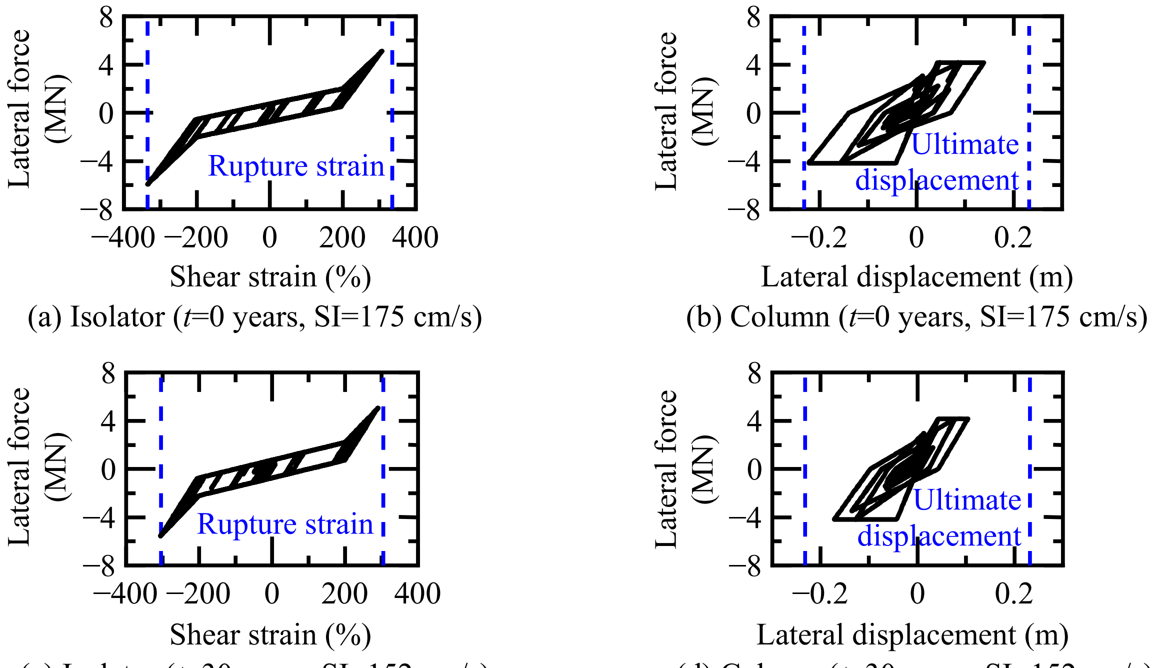
3.1. Failure mode evaluation using mean values

To investigate effects of deterioration of isolators on the seismic failure modes and seismic safety of isolated bridges, response of the target bridges subjected to NS component of JMA Kobe record during the 1995 Kobe earthquake was evaluated with different intensity by varying amplitude of the ground motion. Dynamic response analysis was conducted using the mean values listed in Table 5.

Figure 2 shows the response of the isolated bridges under the ground motion with SI of 95 cm/s. It is confirmed that isolators yield in advance and the response of columns are in elastic under the design ground motion according to the design concept.

Figure 3 shows the response of Bridge A, which have the lowest ultimate capacity ratio R_{QU}. Intensity of the ground motion is adjusted so that the isolator or the column reaches the ultimate limit state. It is shown that rupture of the isolator occurs before the response of the column reaches the ultimate displacement if the isolator is sound. The critical member is also the isolator if the isolator is deteriorated as shown in Figures 3 (c) and (d). Furthermore, it is noted that adjusted SI is decreased from 175 cm/s (t=0 years) to 152 cm/s (t=30 years). This is because the rupture strain of the isolator is decreased by aging deterioration as shown in Figures 3 (a) and (c).

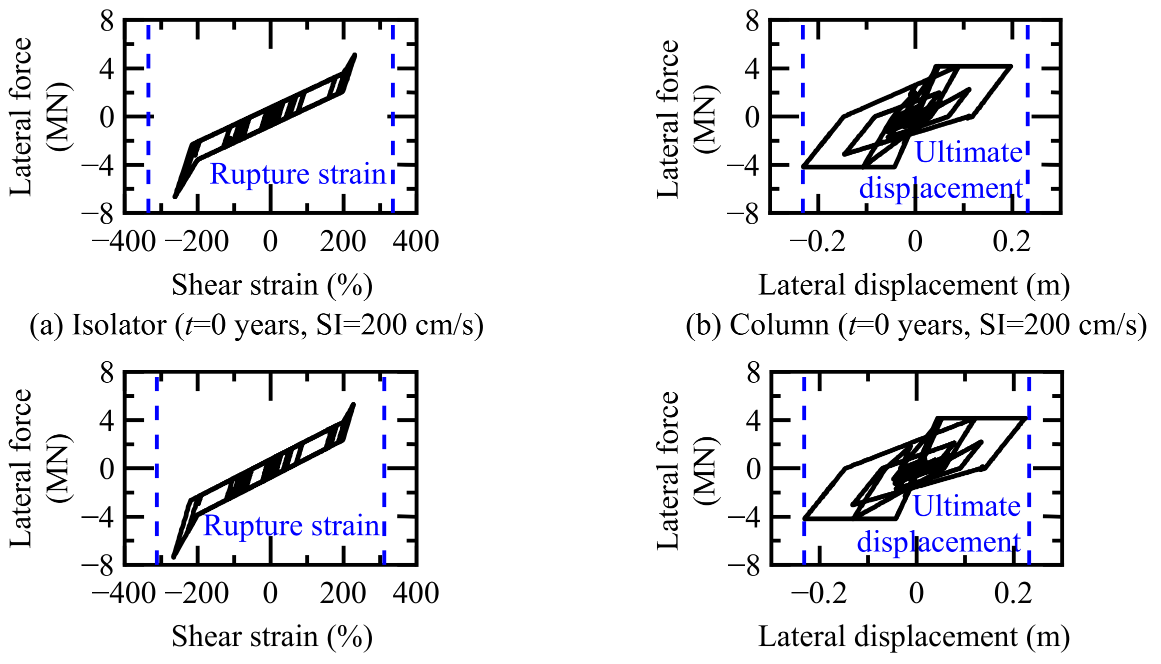
Figure 4 shows the response of Bridge D, which have the highest ultimate capacity ratio



(a) Isolator (t=0 years, SI=175 cm/s) (b) Column (t=0 years, SI=175 cm/s)

(c) Isolator (t=30 years, SI=152 cm/s) (d) Column (t=30 years, SI=152 cm/s)

Figure 3: Response of isolated bridges with the lowest ultimate capacity ratio between the isolator and the column subjected to NS component of JMA Kobe record (Bridge A).



(a) Isolator (t=0 years, SI=200 cm/s) (b) Column (t=0 years, SI=200 cm/s)

(c) Isolator (t=30 years, SI=197 cm/s) (d) Column (t=30 years, SI=197 cm/s)

Figure 4: Response of isolated bridges with the highest ultimate capacity ratio between the isolator and the column subjected to NS component of JMA Kobe record (Bridge D).

R_{QU}. Intensity of the ground motion is adjusted so that the isolator or the column reaches the ultimate limit state. It is noted that the ultimate limit state of the bridge system is determined by

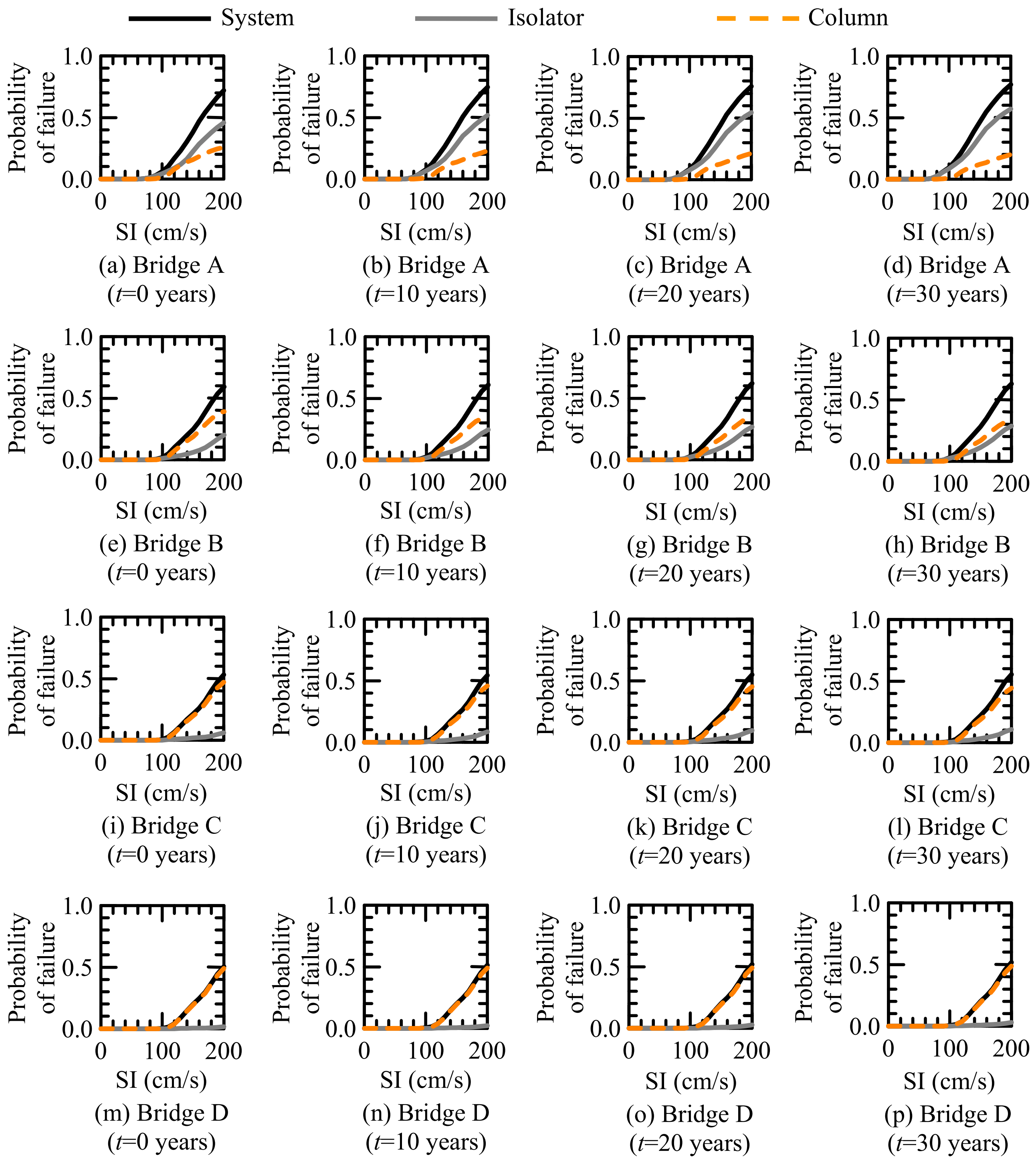


Figure 5: Effects of deterioration of the isolators on the probability of failure of isolated bridges.

the failure of the column and that rupture of the isolator is prevented by the hierarchization of ultimate strength between the isolator and the column. Thus it is also noted that adjusted SI is almost same even if the isolator has been deteriorated for 30 years, because the rupture strain of the isolator does not affect the failure of the bridge system.

3.2. Fragility analysis

Fragility curves for the target bridges at t=0, 10, 20 and 30 years are shown in Figure 5. Rupture of the isolator is inevitable for Bridge A due to the lowest R_{QU} even if the isolator is sound. Failure probability at the isolator decreases as R_{QU} increases. Furthermore, it is noted that failure probability as the bridge system is decreased as R_{QU} increases. By inducing adequate hierarchization of the ultimate strength between the isolator and the column, rupture of the isolators can be prevented and the seismic safety and reparability of isolated bridge systems can be enhanced.

4. CONCLUSIONS

Seismic failure modes and seismic safety of isolated bridges considering long-term deterioration of isolators were investigated based on dynamic response analysis and fragility analysis considering uncertainties in the material and mechanical properties as well as strain hardening of isolators in large shear strain range. The following conclusions were drawn:

1) Effects of long-term deterioration of isolators on the seismic safety of isolated bridges are significant if the ultimate capacity ratio between the isolator and the column is low. This is because failure of the bridge system is determined by rupture of the isolator.
2) By inducing adequate hierarchization of the ultimate strength between the isolator and the column, rupture of the isolators can be prevented and the seismic safety and reparability of bridge systems can be enhanced. This is because the rupture strain of the isolator does not affect the failure of the bridge system if adequate hierarchization is realized.

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