SEISMIC BEHAVIOR OF A SIX-SPAN SIMPLY SUPPORTED BRIDGE WITH MULTIPLE UNSEATING PREVENTION DEVICES

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ABSTRACT

In earthquake-prone areas, a bridge is unavoidably attacked by an earthquake which has been noticed as the most frightened and destructive phenomenon of nature. Observed from the damaged bridges, column failure and deck unseating caused a more serious loss. The purpose of this study is to clarify the effectiveness of multiple unseating prevention devices for bridge by numerical simulations. The Vector Form Intrinsic Finite Element (VFIFE) is selected to be the analysis method, because it is superior in managing the engineering problems with material nonlinearity, discontinuity, large deformation, large displacement and arbitrary rigid body motions of deformable bodies. A six-span simply-supported bridge with rigid bearings and multiple unseating prevention devices (restrainer and stopper) is analyzed under near-field ground motions recorded at JR Takatory and JMA Kobe during the 1995 Japan Kobe earthquake. From the numerical analysis, it is found that installation of multiple unseating prevention devices is not effective to reduce unseating of the simple-supported bridge.

Key words : bridge, failure mechanism, restrainer, stopper, unseating prevention device, vector form intrinsic finite element

INTRODUCTION

In earthquake-prone areas, a bridge is unavoidably attacked by an earthquake which has been noticed as the most frightened and destructive phenomenon of nature. There is high uncertainty about when, where and how large the next earthquake will occur. If an extreme earthquake occurs in a populated area, it may cause numerous deaths, injuries, and property damages. Once bridges collapse during earthquakes, it will also seriously affect the relief transportation for the victims and rehabilitation work.

In the past large earthquakes, such as the 1923 Japan Kanto Earthquake, the 1995 Japan Kobe earthquake, and the 1999 Taiwan Chi-Chi earthquake, a number of bridges suffered damage and even collapsed. Recent earthquakes have highlighted the major problem of unseating due to excessive relative deck displacements during an earthquake (Schiff, 1998). Based on Bridge Damage States (FEMA, 2002), the collapse level of bridges could be identified by unseating of deck, collapsing of any column, or tilting the substructure due to foundation failure. Through the past experiences, it is demanded to understand the failure mechanism of bridges and to develop a better seismic design method for reducing the damage of bridges under earthquakes.

The Vector Form Intrinsic Finite Element (VFIFE) as a new computational method was developed by Ting et al. (2004). It has been recognized as a superior in managing the engineering problems with material nonlinearity, discontinuity, large deformation, large displacement and arbitrary rigid body motions of deformable bodies. VFIFE has been adopted to successfully simulate the ultimate state of isolated and non-isolated bridges with unseating prevention devices by Lee et al. (2009). Nowadays, more than one type of unseating prevention devices are installed in bridges.

AIMS OF STUDY

This study is aimed to study the effectiveness of multiple unseating prevention devices in bridges through ultimate analysis by using VFIFE.

LITERATURE REVIEW

Vector Form Intrinsic Finite Element

The Vector Form Intrinsic Finite Element is based on theory of physics mainly to simulate failure response of a structural system due to applied loads. Assume that a structural system consists of a finite number of particles with mass, which are connected by deformable elements without mass. A particle designated as α has a mass value $\mathbf{M}_\alpha$ and a displacement $\mathbf{d}_\alpha(t)$ at time t. Applying Newton's Second Law of Motion, the equations of motion for particle α is

$$\mathbf{M}_\alpha \frac{d^2\mathbf{d}_\alpha(t)}{dt^2} = \mathbf{P}_\alpha - \mathbf{f}_\alpha \qquad (1)$$

$\alpha = 1,2,3,\ldots,N$

where $\mathbf{P}_\alpha$ is the applied force or equivalent force acting on the particle; $\mathbf{f}_\alpha$ is the total resistance force exerted by the elements surrounding the particle, or the internal force. N is taken as the total number of mass particles in the system including all the sub-structures. Each element without mass is in static equilibrium.

$$\sum_e \mathbf{f}_e = 0 \qquad (2)$$

where $\mathbf{f}_e$ is the element internal forces.

Unseating Prevention Devices

An unseating prevention device is a component connecting the uperstructure and substructure or superstructure, providing restraining force against unseating of superstructure. Unseating of superstructure is the most serious damage for bridges. Therefore, unseating prevention systems are developed to avoid unseating of bridges including the seating length of the girder on the top of cap beam, unseating prevention devices and components limiting excessive displacement.

Many studies of unseating prevention devices have been carried out by researchers to understand the influencing factor on the behavior of unseating prevention devices and then to provide appropriate design procedures. Since the 1995 Japan Kobe earthquake and the 1999 Taiwan Chi-Chi earthquake, multiple unseating prevention devices have been installed on bridges to increase the capacity for preventing excessive displacements and unseating. The design force and gap spacing for restrainers or concrete shear keys are the major parameters. It is found that properly adopting the design force and gap spacing for shear keys limits the damage of bridge columns under the design earthquake (Liu and Chang, 2006). With shorter gap spacing, the bridge column may suffer more damage. Moreover, the restrainer should not exceed its breaking strain and the deck should have a sufficient unseating length under the design earthquake.

METHODS

Model Descriptions

The bridge is designed based on Japan Highway Bridge Design Codes. As shown in **Fig. 1**, the bridges consist of a six-span deck with a total length of 6@40 m = 240 m and a width of 12 m. The superstructure of the target bridges consists of five steel I girders and a reinforced-concrete slab with pile foundations to support it. The height of reinforced-concrete columns is 10 m with two abutments. The view of superstructure, column, pile configuration and dimensions are shown in **Fig. 2**.

The deck is transformed into one having steel material with modulus of elasticity E = 2.04 x 10^7 t/m. The section area A = 0.585 m^2 and moment of inertia I_y = 0.295 m^4. Total weight W of the deck per a span is 600 tf.

Design for each material property can be seen in **Table 1**.

Table 1. Unseating prevention devices

No.	Properties of material	Restrainer	Stopper
1	Materials	6 unit PC cable	concrete box
2	Dimension	Ø 1 in	
3	Area A , mm^2	519.300	
4	Hook or gap length, m	0.1, 0.2, 0.3, 0.4	0.1, 0.2, 0.3, 0.4
5	Ultimate design strength, tf	569.85	500 & 650
7	Stiffness, tf/m	23630.53	298350

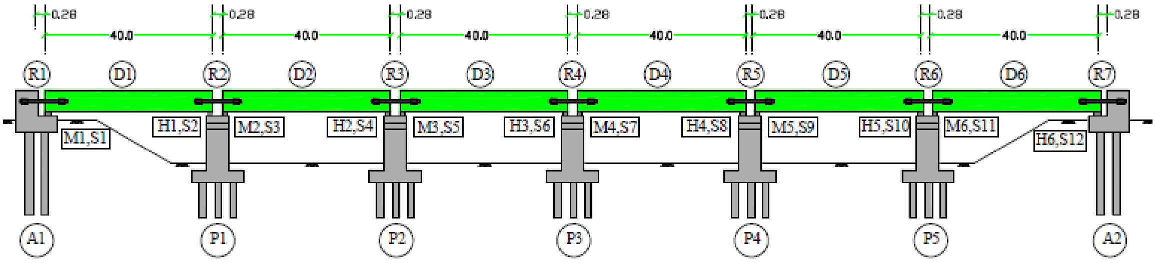


Figure 1. A six-span simply-supported bridge with restrainers, stoppers and rigid bearings

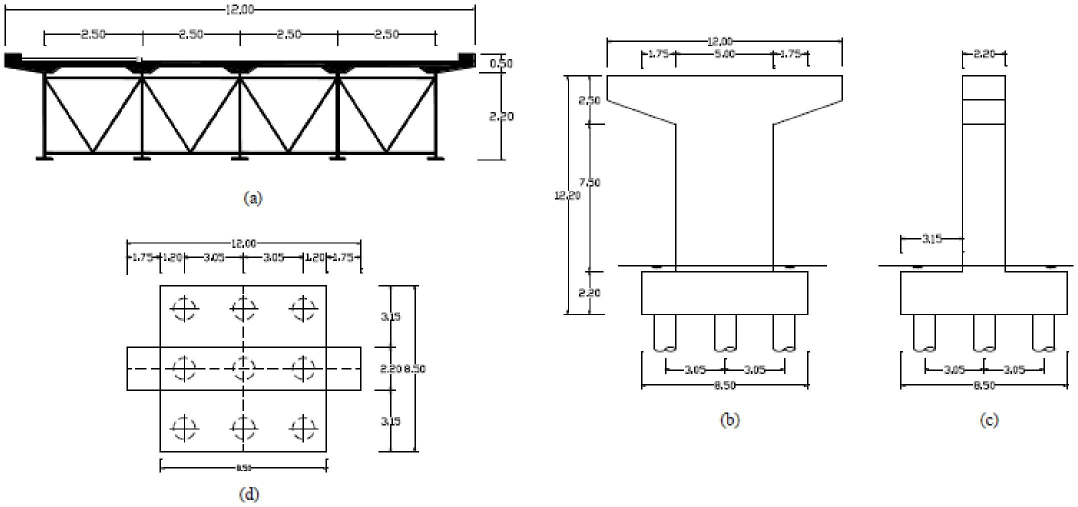


Figure 2. (a) Lateral view of superstructure, (b) lateral view of column, (c) side view of column, and (d) pile configuration

The ground motions recorded at JR Takatory station and JMA Kobe during the 1995 Japan Kobe earthquake, are selected to investigate the seismic behavior of the target bridge, as shown in **Fig. 3**. The peak ground acceleration is 6.66 m/s^2 and 8.18 m/s^2. To investigate the ultimate state of bridges, the magnitude of ground motions is amplified from 100% to 300% at an increment of 10%.

Lee et al. (2008) have developed two nonlinear elements in two-dimensions in VFIFE, a bilinear element and a spring element with a gap or a hook. A gap and a hook spring element with fracture strength are used to simulate the behavior of stoppers and restrainers, respectively. The gap/impact spring element is used to simulate the pounding between adjacent decks. The ultimate strength of restrainers and stoppers shall be taken as much as 1.5 times the dead load reaction.

The target bridge will be analyzed with different combinations of the stopper gap and the restrainer hook. One case consists of restrainers with fixed hook 40 cm and stoppers with gaps varying from 10 cm to 40 cm at an increment of 10 cm. The other case consists of stoppers with fixed gap 40 cm and restrainers with hook varying from 10 cm to 40 cm at an increment of 10 cm.

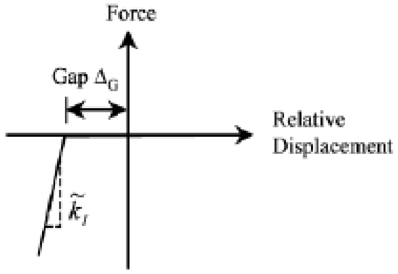


Figure 3. Relationship between force and relative displacement for impact-spring elemen (this picture is taken from paper by Ruangrassame and Kawashima, 2003)

Method of analysis

In order to predict the ultimate state of bridges with multiple unseating prevention devices through numerical analysis and to find a suitable combination of different types of restrainers for protecting the deck of bridges from unseating, the target bridge will be analyzed with different combinations of the stopper's gap and the restrainer's hook. The Vector Form Intrinsic Finite Element (VFIFE) is selected to be the analysis method.

SIMULATION RESULTS AND DISCUSSION

Failure Sequence

Assume the bridge with 10 cm of the gap for the stoppers and 40 cm of the hook for the restrainers is excited by 170% of JR Takatory ground motion. The total numbers of the stoppers, restrainers, and hinge bearings are 12, 7, and 6, respectively.

In the design philosophy of this bridge, the failure strength of the hinge bearings is less than that of the stoppers. The failure strength of the stoppers is less than that of the restrainers. Also the size of the gap of the stoppers is smaller than that of the hook of the restrainers. The unseating of the decks can be attributed to the excessive relative displacement which is larger than the seating length on the top of the cap beam.

Through numerical simulation, the failure sequence of the target bridge can be seen in **Fig. 4**. Then, the trigger and failure times of the stoppers and restrainers are shown in **Tables 2(a)** and **(b).** The failure time and ductility demand of the columns are shown in **Table 2(c).** Also the failure time of the hinge bearings and unseating time of the decks are presented in **Table 2(d).**

It is found that the hinge bearing H6 on the right abutment fails first and then the other hinge bearings successively fail in the early time of earthquake excitations. Then the stoppers are triggered to limit the deck displacement. However, the stoppers fail just after their trigger. It is interesting that the decks D3 and D5 unseat first and then cause the failure of the restrainers R4 and R6. It is noticed that the stoppers and restrainers cannot provide the expected function to prevent the unseating of the decks. Since the ductility demand of all columns is less than the ultimate ductility, no columns collapse during the ground motion.

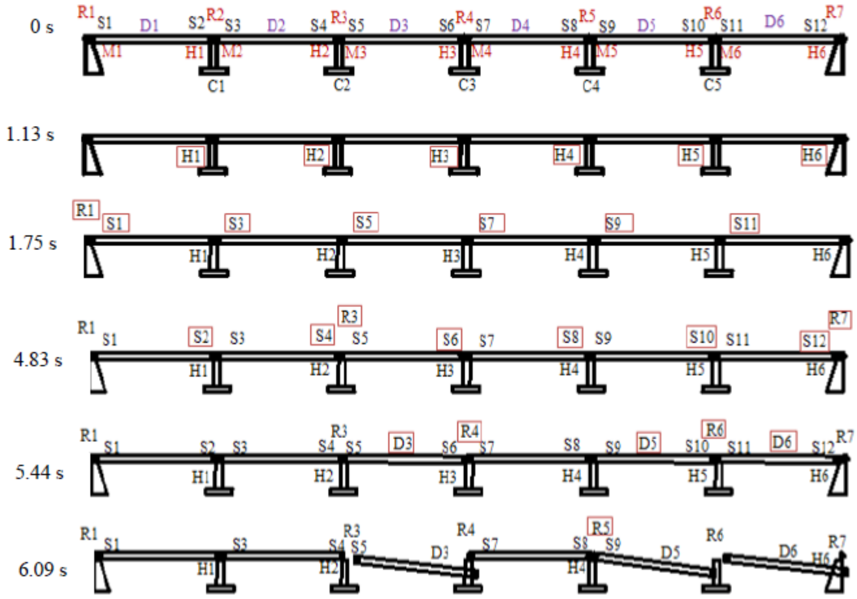


Figure 4. Failure sequences for the target bridge with restrainers (hook is 40 cm) and stoppers (gap is 10 cm) under 170% of JR Takatory record.

Table 2. The failure time of the bridge devices

a. Failure time of the stoppers

No	Start (sec)	Failure (sec)
S1	1.47	1.47
S2	2.77	2.77
S3	1.43	1.44
S4	3.08	3.08
S5	1.46	1.46
S6	2.49	2.49
S7	1.57	1.57
S8	3.69	3.71
S9	1.44	1.45
S10	4.83	4.83
S11	1.73	1.73
S12	2.37	2.37

b. Failure time of the restrainers

No	Start (sec)	Failure (sec)
R1	1.74	1.75
R2	-	-
R3	3.12	3.14
R4	5.43	5.44
R5	6.08	6.09
R6	5.31	5.31
R7	4.68	4.69

c. Columns failure

No	Failure (sec)	Column Ductility
C1	-	15.58
C2	-	15.15
C3	-	15.55
C4	-	12.29
C5	-	12.92

d. Failure of the hinge bearings and unseating time of the decks

No	Start (sec)	Friction (sec)	Deck No.	Unseating (sec)
H1	0.00	1.02	D1	-
H2	0.00	1.13	D2	-
H3	0.00	1.13	D3	4.94
H4	0.00	0.91	D4	-
H5	0.00	1.13	D5	4.97
H6	0.00	0.81	D6	4.91

Shown in **Table 3** and **Table 4** are the result of unseated decks and column failure for bridge under JR Takatory record, respectively. The increasing number of failed unseating prevention devices is caused by ground motion of earthquake, as shown in **Table 5**. The different ground motion was recorded under JMA Kobe record is used in this study to compare the result of unseated decks, column failure and the number of failed unseating prevention devices, as shown in **Table 6**, **Table 7** and **Table 8**, respectively.

Table 3. Number of unseated decks for the target bridge (hook is 10 cm, gap is 10 to 40 cm) under JR Takatory record

GM Scale	Number of Unseated Decks (Restrainer type 1)				
	R1	R1 & S (gap 10)	R1 & S (gap 20)	R1 & S (gap 30)	R1 & S (gap 40)
100%	0	0	0	0	0
110%	0	0	0	0	0
120%	0	0	0	0	0
130%	0	0	0	0	0
140%	0	0	1	0	0
150%	0	1	1	0	0
160%	2	0	0	0	0
170%	5	3	1	1	2
180%	1	4	0	1	0
190%	3	0	0	0	0
200%	6	4	5	6	6
210%	6	6	6	6	6
220%	3	6	6	6	6
230%	6	6	6	6	6
240%	6	6	6	6	6
250%	6	6	6	6	6
260%	6	6	6	6	6
270%	6	6	6	6	6
280%	6	6	6	6	6
290%	6	6	6	6	6
300%	6	6	6	6	6

Table 4. Number of column failure for the target bridge (hook is 10 cm, gap is 10 to 40 cm) under JR Takatory record

GM Scale	Number of Columns Failure (Restrainer type 1)				
	R1	R1 & S (gap 10)	R1 & S (gap 20)	R1 & S (gap 30)	R1 & S (gap 40)
100%	0	0	0	0	0
110%	0	0	0	0	0
120%	0	0	0	0	0
130%	0	0	0	0	0
140%	0	0	0	0	0
150%	0	0	0	0	0
160%	0	0	0	0	0
170%	0	0	0	0	0
180%	0	0	0	0	0
190%	0	0	0	0	0
200%	0	0	0	0	1
210%	0	0	0	0	0
220%	0	0	0	0	0
230%	0	1	1	2	2
240%	0	4	4	4	4
250%	0	5	5	5	5
260%	0	5	5	5	5
270%	1	5	5	5	5
280%	1	5	5	5	5
290%	5	5	5	5	5
300%	4	5	5	5	5

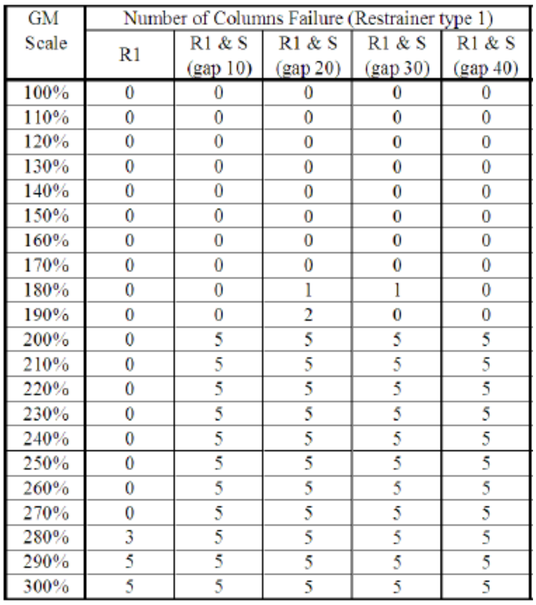
Table 5. Number of failed unseating prevention devices (hook is 10 cm, gap is 10 to 40 cm) for the target bridge under JR Takatory record

GM Scale	Number of Failed Restrainer Type 1 and Stopper								
	R1	Gap 10		Gap 20		Gap 30		Gap 40	
		R1	S	R1	S	R1	S	R1	S
100%	0	1	10	0	9	0	7	0	3
110%	2	2	12	4	12	2	8	2	7
120%	2	2	12	3	11	2	11	2	8
130%	2	2	12	7	12	2	11	2	11
140%	2	3	12	10	12	3	11	3	10
150%	2	3	12	11	12	2	11	2	11
160%	6	2	12	6	12	2	11	3	11
170%	7	6	12	10	12	4	12	4	11
180%	5	7	12	9	12	5	11	5	11
190%	6	4	12	9	12	3	11	2	11
200%	7	7	12	11	12	7	11	7	12
210%	7	7	12	12	11	7	12	7	12
220%	5	7	12	12	12	7	11	7	12
230%	7	7	12	11	11	7	12	7	12
240%	7	7	12	3	8	7	11	7	12
250%	7	7	12	1	12	7	12	7	12
260%	7	6	10	7	9	7	7	7	7
270%	7	7	8	7	8	7	8	7	9
280%	7	6	10	7	10	7	10	6	10
290%	7	7	11	7	11	7	11	7	10
300%	7	7	10	7	9	7	8	7	8

Table 6. Number of unseated decks for the target bridge (hook is 10 cm, gap is 10 to 40 cm) under JMA Kobe record.

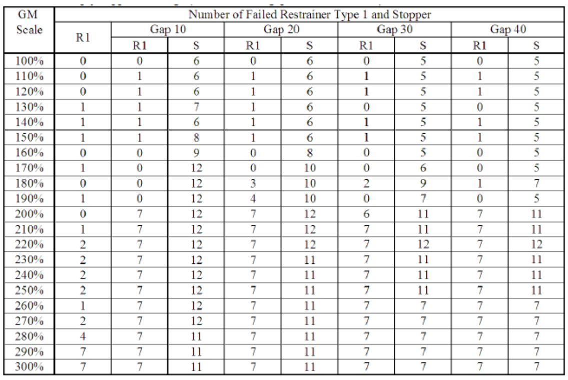
GM Scale	Number of Unseated Decks (Restrainer type 1)				
	R1	R1 & S (gap 10)	R1 & S (gap 20)	R1 & S (gap 30)	R1 & S (gap 40)
100%	0	0	0	0	0
110%	0	0	0	0	0
120%	0	0	0	0	0
130%	0	0	0	0	0
140%	0	0	0	0	0
150%	0	0	0	0	0
160%	0	0	0	0	0
170%	0	0	0	0	0
180%	0	0	2	2	0
190%	0	0	3	0	0
200%	0	6	6	6	6
210%	0	6	6	6	6
220%	0	6	6	6	6
230%	0	6	6	6	6
240%	0	6	6	6	6
250%	0	6	6	6	6
260%	0	6	6	6	6
270%	0	6	6	6	6
280%	5	6	6	6	6
290%	6	6	6	6	6
300%	6	6	6	6	6

Table 7. Number of column failure for the target bridge (hook is 10 cm, gap is 10 to 40 cm) under JMA Kobe record



GM Scale	Number of Columns Failure (Restrainer type 1)				
	R1	R1 & S (gap 10)	R1 & S (gap 20)	R1 & S (gap 30)	R1 & S (gap 40)
100%	0	0	0	0	0
110%	0	0	0	0	0
120%	0	0	0	0	0
130%	0	0	0	0	0
140%	0	0	0	0	0
150%	0	0	0	0	0
160%	0	0	0	0	0
170%	0	0	0	0	0
180%	0	0	1	1	0
190%	0	0	2	0	0
200%	0	5	5	5	5
210%	0	5	5	5	5
220%	0	5	5	5	5
230%	0	5	5	5	5
240%	0	5	5	5	5
250%	0	5	5	5	5
260%	0	5	5	5	5
270%	0	5	5	5	5
280%	3	5	5	5	5
290%	5	5	5	5	5
300%	5	5	5	5	5

Table 8. Number of failed unseating prevention devices (hook is 10 cm, gap is 10 to 40 cm) for the target bridge under JMA Kobe record



GM Scale	Number of Failed Restrainer Type 1 and Stopper								
	R1	Gap 10		Gap 20		Gap 30		Gap 40	
		R1	S	R1	S	R1	S	R1	S
100%	0	0	6	0	6	0	5	0	5
110%	0	1	6	1	6	1	5	1	5
120%	0	1	6	1	6	1	5	1	5
130%	1	1	7	1	6	0	5	0	5
140%	1	1	6	1	6	1	5	1	5
150%	1	1	8	1	6	1	5	1	5
160%	0	0	9	0	8	0	5	0	5
170%	1	0	12	0	10	0	6	0	5
180%	0	0	12	3	10	2	9	1	7
190%	1	0	12	4	10	0	7	0	5
200%	0	7	12	7	12	6	11	7	11
210%	1	7	12	7	12	7	11	7	11
220%	2	7	12	7	12	7	12	7	12
230%	2	7	12	7	11	7	11	7	11
240%	2	7	12	7	11	7	11	7	11
250%	2	7	12	7	11	7	11	7	11
260%	1	7	12	7	11	7	7	7	7
270%	2	7	12	7	11	7	7	7	7
280%	4	7	11	7	11	7	7	7	7
290%	7	7	11	7	11	7	7	7	7
300%	7	7	11	7	11	7	7	7	7

Comparisons & Discussions

The result of unseated decks and columns failure will be analyzed for the target bridge under JR Takatory record and JMA Kobe record.

As shown in **Table 3**, the target bridge with restrainers (R1), restrainers and stoppers (R1+S) suffer unseating of the superstructure in the first time as the ground motion is amplified equal to 160% and 140%, respectively. Columns collapse under 270% and 230%, respectively. The collapse of the target bridge is due to insufficient unseating prevention length when the ground motion is amplified equal and larger than 140% to 210%. If the amplification is larger than 210%, the collapse is attributed to column failure.

As shown in **Table 6**, the target bridge with restrainers (R1) under JMA Kobe record, restrainers and stoppers (R1+S) suffer unseating of the superstructure in the first time as the ground motion is amplified equal to 280% and 180%, respectively. Collapsing of the column occur under the same ground motion with unseating of the superstructure, 280% and 180%, respectively. It represents that almost unseating of the decks are caused by the column failure. When the ductility demand exceeds the ultimate ductility, column collapse and unseating of the decks which is supported by this column occur.

The amplification of ground motion is followed by the rising number of unseated decks and columns failure, although the different result is happened in some cases. This condition is caused by unpredictable and complicated characteristic of earthquake, for each rising magnitude.

CONCLUSIONS

The total 21 amplifications of the ground motions were studied to investigate seismic response of a simply supported bridge with different type of unseating prevention devices (restrainers and stoppers) by using VFIFE. Observed from the result of numerical simulations, several conclusions are listed in the following:

a. The collapse of the simply-supported bridge is due to insufficient unseating prevention length under larger than 130% of the JR Takatory record. However, when the ground motions are larger than 220%, the failure of the entire bridge commences with failure of columns.

b. The collapse of the the simply-supported bridge under JMA Kobe record is due to failure of columns.
c. Installation of multiple unseating prevention devices leads earlier unseating of the superstructure.

The effectiveness of multiple unseating prevention devices can be further investigated for the different type of the bridge and different ground motion. Besides, it is important to define an adequate length for the hook of restrainers and the gap of the stoppers to design a bridge against earthquake.

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