Seismic Protection for Multiple Span Continuous Steel Bridges using Shape Memory Alloy-Restrainer-Dampers

형상기억합금을 이용한 다경간 연속 강교량의 지진보호

최 은 수* 김 학 수**

Eunsoo Choi Haksoo Kim

국문요약

본 논문은 강교좌장치를 가지고 있는 연속 강교량을 지진으로부터 보호하기 위해서 형상기억합금을 이용한 장치를 제안했다. 예로 사용하고 있는 연속 강교량은 고정단을 가진 교각에 지진하중이 집중하고 상당히 큰 상부구조의 중량으로 인하여 교각에 손상을 입기 쉽고 상판의 교대에 대한 충돌로 교대의 수동변위가 크게 나타날 수 있다. 본 연구에서는 두 가지 종류의 restrainer-damper가 제안되었으며 지진해석을 통해서 효과를 검증하였다. 또한 미주에서 일반적으로 사용되고 있는 강재 케이블의 restrainer와 성능을 비교하였다.

주요어 : 지진보호, 교량, 형상기억합금, restrainer

ABSTRACT

This paper introduces a shape memory alloy-restrainer-damper(SMA-RD) to protect multiple span continuous steel bridges from seismic loads. The type of bridges has only one fixed bearing condition on a pier and expansion bearings are located on the other piers and abutments. Due to this state and a big mass of the deck, these bridges are usually very vulnerable to column's damage on which fixed bearings are located and large deformation of abutments in passive action. Two types of SMA-RDs are developed, and their effect is inspected for protecting the bridges through seismic analyses. Conventional steel restrainer cables are also used to reduce the seismic vulnerability of the bridge and the results are compared to those of the SMA-RDs.

Key words : seismic protection, bridges, shape memory alloy, restrainers

1. Introduction

Multiple span continuous(MSC) steel bridges shown in Fig. 1 are very common in the central and southeastern of the United States. A lot of them built before 1990 does not have appropriate seismic resistance since they were constructed against low seismic loads. Therefore, a seismic retrofit is required to increase their resistance capacity against expected earthquakes. General retrofit measures are elastomeric bearings, lead-rubber bearings, restrainer cables, or lock-up devices that are activated to lock an expansion condition during an earthquake. An enough height should be secured to replace steel bearings by elastomeric bearings or lead-rubber bearings. General rocker steel bearings shown in Fig. 2 can give enough height for elastomeric or lead-rubber bearings. However, low types of steel bearings are too small to propose the height for the isolation bearings. Alternatives for the cases can be used such as restrainer cables and lock-up devices. Restrainer cables are established between decks and pier caps or decks and abutments. At normal state a lock-up device can move without any resistance and thus can absorb thermal expansion of decks. However, during an earthquake, it restricts any movement and acts like a fixed bearing. Due to this fact, the lock-up device can be placed only between decks and pier caps. The locked device can transfer seismic loads from decks to piers like a fixed steel bearing. Considering the continuous bridge in Fig. 1 retrofitted by lock-up devices, both columns have a fixed condition during an earthquake. However, Choi's study(1) showed that the bridge having a fixed condition on both columns are still vulnerable to the expected ground motions in the area. Therefore, it can be assumed that the lock-up devices are not adequate to protect the multiple span continuous steel bridges from seismic loads.

Bridge restrainers are intended to limit the relative movements at expansion joints and prevent the loss of supports. Restrainers can be in the form of plates, rods, or cables. The most common type of restrainers in the United States is the steel restrainer cable. Restrainer cables were first employed in the United States by California Department of Transportation(Caltrans) following the 1971 San Fernando Earthquake.(2) The 1971 San Fernando earthquake in California resulted in numerous highway bridges collapses because

* 정회원 · 철도기술연구원, 궤도토목연구본부, 선임연구원
(대표저자 : eunsoochoi@krri.re.kr)
** 호남대학교, 토목공학과, 부교수

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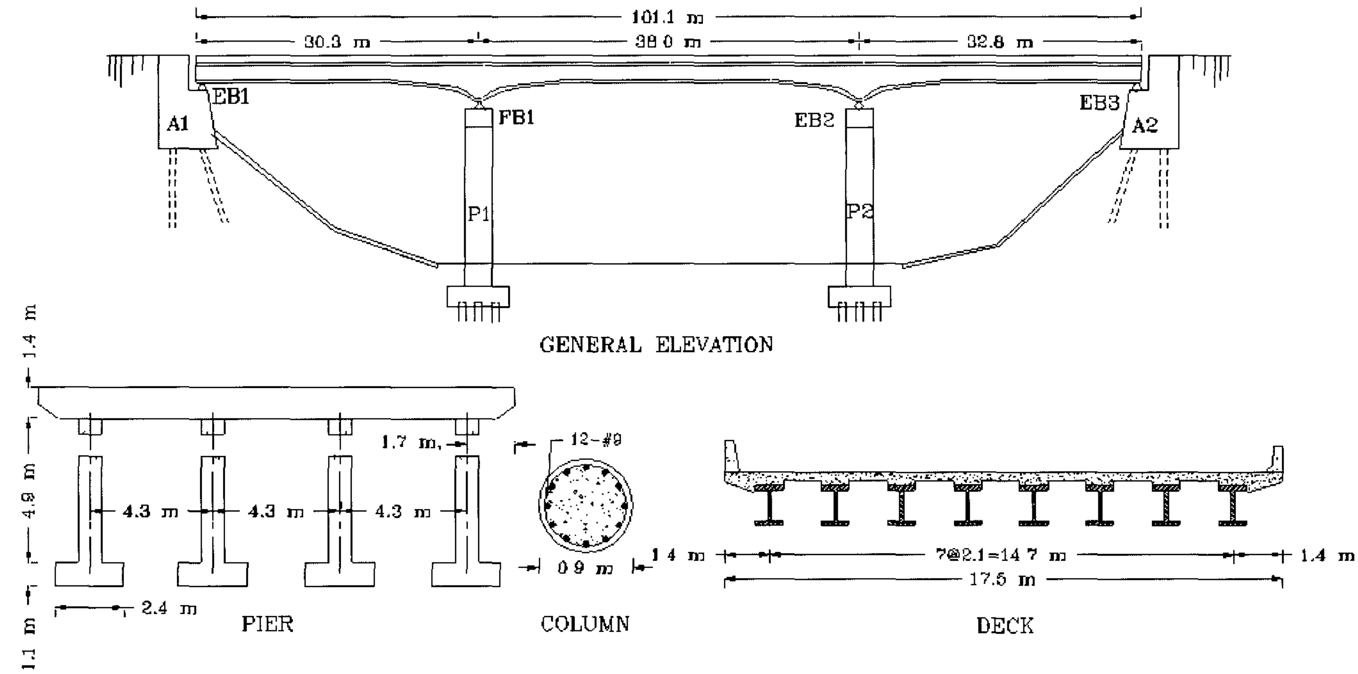


Fig. 1 Shape of a typical multiple span continuous steel bridge

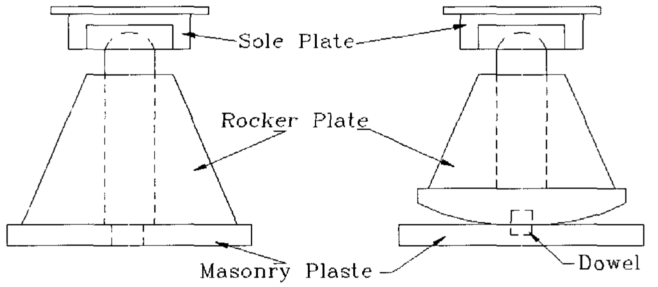


Fig. 2 General shape of steel rocker bearings(fixed and expansion type)

of excessive longitudinal movements at expansion joints and supports. Since then, Caltrans initiated a retrofit program consisting of using restrainer cables at internal hinges of bridges with short seat widths. Approximately 1400 bridges were retrofitted under the Caltrans Phase I retrofit program.[(3)] The performance of restrainer cables was tested in the past earthquakes such as the 1989 Loma Prieta Earthquake and the 1994 Northridge Earthquake in California. They mostly performed adequately, but some bridges were damaged or collapsed.[(3)-(5)] Several states in the central and southeastern of the United States including Tennessee, Illinois, and Missouri have recently begun using restrainer cables. Indiana and South Carolina plan to incorporate restrainers in the design of bridges in the near future.[(6)] Thus, this study intends to use restrainer steel cables for the MSC steel bridge as a retrofit measure.

Shape memory alloy(SMA) bars or wires can be used for restrainers or dampers to increase the seismic resistance of bridges. Dolce et al.[(7)] developed a seismic damper using pre-strain SMA wires. DesRoches and Delemont[(8)] used SMA bars to reduce the relative displacement in a multiple span simply supported bridge and compared the results to those of restrainer steel cables. Wilde et al.[(9)] developed a model of SMA behavior and used the model of SMA bars for the analysis to restrict transverse displacement of a bridge.

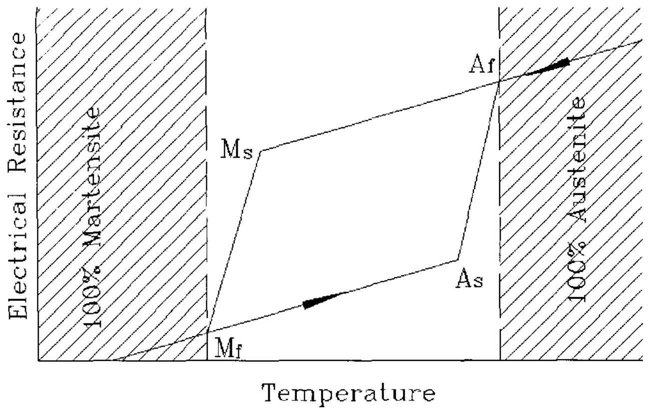
This study will propose two types of SMA-restrainer-dampers(SMA-RD) to reduce the seismic vulnerability of the bridge. Through seismic analyses for a MSC steel bridge shown in Fig. 1, the effect of the two SMA-RDs will be examined and the bridge responses with SMA-RDs will be compared to those of as-built bridge and the bridge retrofitted by restrainer steel cables.

2. Characteristics of shape memory alloy

Shape memory is able to recover a deformed shape to the original, even after rather large deformations. Once deformed at low temperature, the materials maintain the deformed shape until heated, while they return to the original shape. This unique "shape memory" characteristics is a result of a martensite phase transformation that can be temperature induced or stress-induced.

The SMA has two phases of martensite and austenite that depends on temperature variation. Fig. 3 shows the phase transformation due to temperature variation. When the alloy is deformed below M_f, it retains the deformation until heated. The shape recovery starts at A_s and is completed at A_f.

Normally on cooling, the martensite starts to form at M_s under no stress. However, in the same material, martensite



Where M_s : martensite start temperature

M_f : martensite finish temperature

A_s : start of reverse transformation of martensite

A_f : finish of reverse transformation of martensite

Fig. 3 The shape memory effect is described with reference to a plot of electrical resistance vs. temperature from which characteristics transformation temperatures M_s, M_f, A_s and A_f are determined(Duerig et al., 1990).

can begin above M_s if a stress is applied, and the martensite so-formed is termed stress-induced martensite(SIM). This phase is temperature independent; that is another type of shape memory known as superelasticity. Above M_s the stress required to produce SIM increases with increasing temperature. The difficulty to produce SIM increases continuously with increasing temperature until M_d; that is the highest temperature at which it is possible to have martensite.

In general, the alloy of Nickel and Titanium named Nitinol is used widely for engineering aspects although several alloys such as Copper alloy show the effect of shape memory.[8] Nitinol shape memory alloys possess several desirable properties as a restrainer-damper in bridges as shown in Fig. 4 where shows a three dimensional relationship of stress-strain-temperature. Fig. 5 shows the behavior of a SMA wire used in this study.

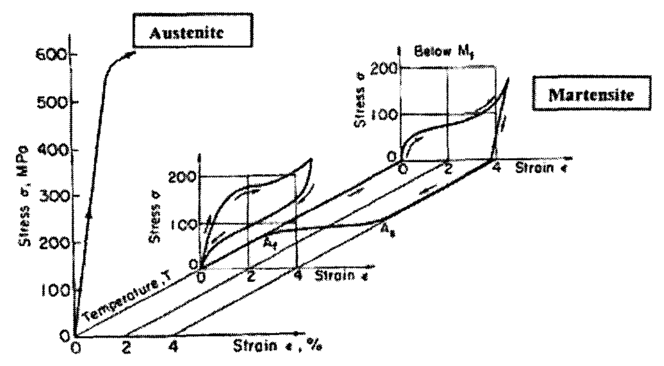


Fig. 4 Three-dimnesional stress-strain-temperature diagram showing the deformation and shape memory behavior of a Nitinol deformed below M_f, above A_f and above M_d.[10]

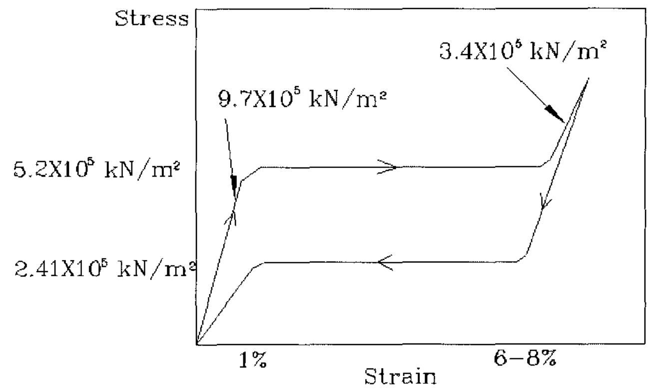


Fig. 5 Hysteresis of a SMA wire used for SMA-RDs[8]

3. Shape memory alloy-restrainer-damper(SMA-RD)

Restrainer cables installed in a bridge use only the capacity of abutments in pulling action. However, their ultimate capacity in pulling is generally smaller than that in pushing as illustrated in Fig. 6 that shows the behavior of the abutment in the example bridge in pulling and pushing action. The ultimate force in pushing is 15830kN that is 5.24 times of the ultimate force in pulling, 3023kN. Therefore, it may give more benefit to use the pushing capacity or the both capacities in pushing and pulling than the utilization of the pulling capacity only.

A restrainer-damper using shape memory alloy wires proposed in this paper can use both capacities of an abutment in pulling and pushing. The SMA wires used in this study are prestrained to remove the first elastic range in Fig. 5; which can be obtained by stressing the wires to about 1% strain. The basic shape of the device is suggested in Fig. 7. SMA wires wrap the main and the sliding frames. The main frames are attached under a bridge girder and the sliding one is pushed by a pushing bracket attached to the piston that is connected to pier cap beams or abutments. At

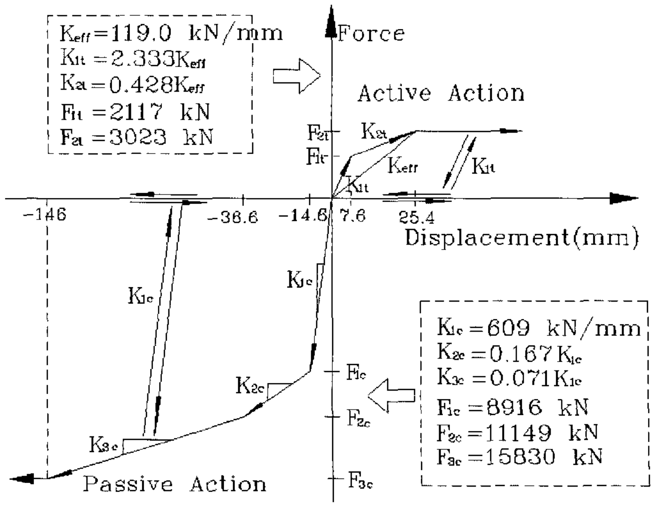


Fig. 6 Analytical behavior of an abutment in the example bridge

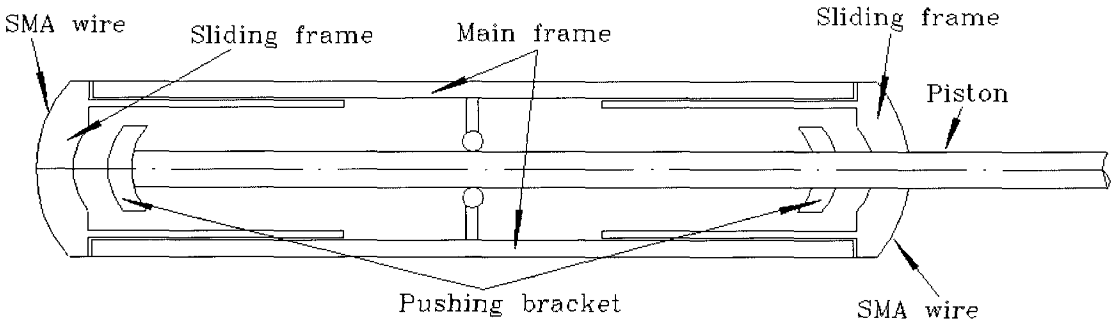


Fig. 7 Shape of a restrainer-damper using shape memory alloy wires

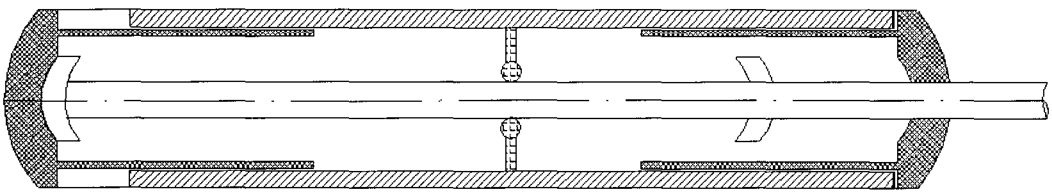


Fig. 8 Shape of a SMA-RD activated

the same time, the SMA wires are strained. A gap can be located between the sliding frame and the pushing bracket to absorb thermal expansion of decks. Fig. 8 shows the shape of a SMA-RD activated in left direction and the device can be also activated in the opposite direction. When one of the two pushing brackets is removed, the SMA-RD is activated only in one-way direction, pushing or pulling. This study will introduce two types of SMA-RDs: 1) one is activated in pushing and pulling action; and 2) the other is activated only in pushing direction.

4. Analytical model of a MSC steel bridge

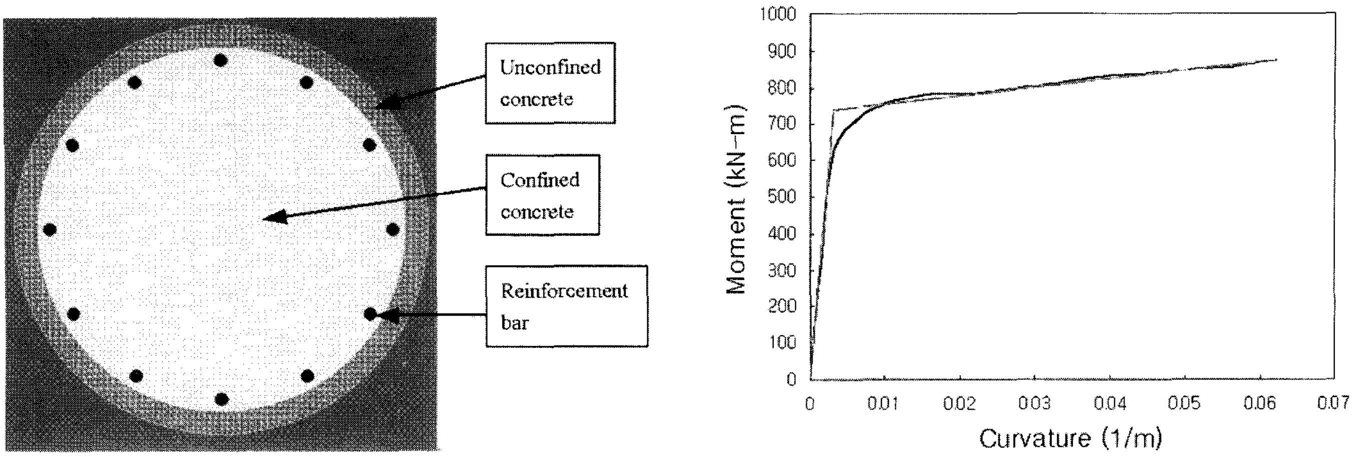
A three-span continuous steel bridge as shown in Fig. 1 is modeled for this study. The bridge has an array of fixed steel bearings on the first pier (P1) and expansion steel bearings on the other locations(A1, A2, and P2). The bridges consist of several components such as columns, abutments, steel bearings, foundations, and superstructures; some of them, particularly columns and bearings, exhibit highly nonlinear behavior. Therefore, two-dimensional non-linear analytical model of the bridge in longitudinal direction is developed using DRAIN-2DX nonlinear analysis program.[11] The superstructure is usually expected to remain linear under longitudinal earthquake motions so that it is modeled using a linear element. In the bridge model, abutments are modeled with multiple line plastic behavior. Columns consist of 22 fiber elements for unconfined and confined concrete and reinforcements. The pile foundations are modeled with linear springs for horizontal and rotational direction. Mander's test results[12] are used for modeling the fixed and expansion bearings. The gap of 76mm at abutments, which is from the design drawings, is modeled with trilinear elastic element to simulate the pounding between deck and abutment.[1]

For calculating the yield curvature of the columns, UCFyber, which uses Mander's model for unconfined and confined concrete[13], models the column's section as shown in Fig. 9(a) using thousands of fiber elements for unconfined and confined concrete and reinforcements. The effective yield curvature is estimated as 3.28e-3 1/m, as shown in Fig. 9(b), which will be used to calculate the curvature ductility of columns.

5. Responses of the as-built and retrofitted bridge by restrainer cables

At first, the responses of the as-built bridge are estimated and then the results of the restrainer cables are proposed. Comparing these results, the effect of the cables will be assessed to increase the seismic resistance of the bridge. For these analyses, El Centro ground motion, whose original PGA is 0.34g, is used with scaling from weak to strong such as 0.2, 0.4, 0.6, and 0.8g PGA.

Restrainer cables are installed between the deck and abutments or piers where expansion bearings are located. Fig. 10 shows the shape of a restrainer cable generally used in California of the United States. The analytical model of a restrainer cable is shown in Fig. 11; 1) the elastic stiffness is 6.42kN/mm, 2) the hardening ratio is 0.05, 3) the yield force is 174kN, and 4) the slack is 6.35mm which is generally introduced to avoid any fatigue problem by the thermal expansion at expansion joints. A cable is



(a) UCFyber model of the cross-section of a column (b) Moment-curvature relationship for a column

Fig. 9 Fiber element model and its moment-curvature relationship for a column

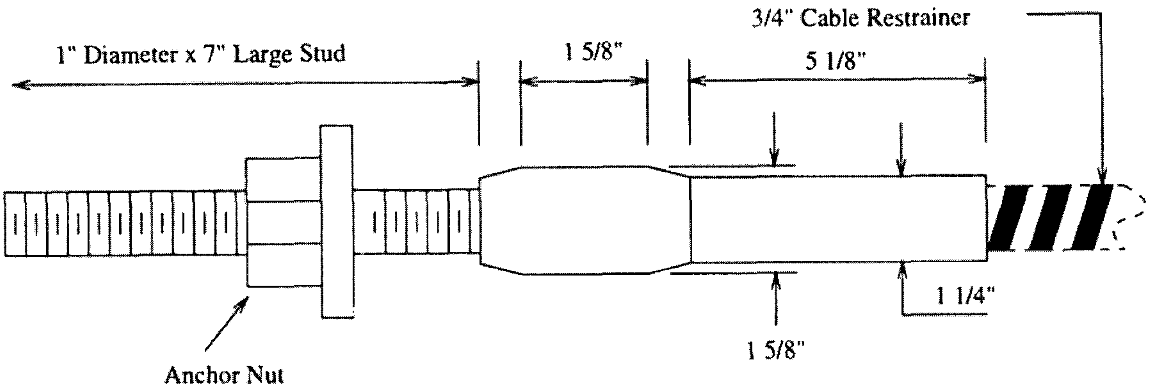


Fig. 10 Shape of a restrainer cable used in California of United States

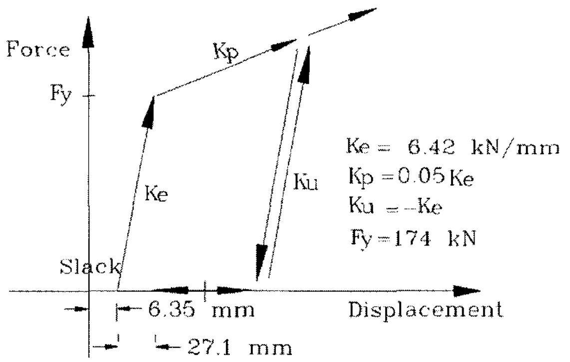


Fig. 11 Analytical model of a restrainer cable

installed for each girder and the total is 8 cables.

The concerned responses of the two bridges are proposed in Table 1: where 1) the ductility is curvature ductility; 2) the pier drift ratio is the per cent of the top displacement of a column to the column's length; 3) the opening is the relative displacement between the deck and abutments; 4) for the abutment deformation, (+) stands for active deformation and (-) does passive deformation.

For the as-built bridge seismic demands concentrate on the column with fixed bearings, however, restrainer cables distribute the demands to both columns. For the moderate ground motion of 0.4g PGA the maximum ductility decreases by 9.8% with the cables and the maximum opening also decreases by 14.2%. However, the active deformations of abutments increase by about 7 times since the cables transfer large forces to them in active action. The cables prevent the pounding between the deck and the abutments and reduce the passive deformation of the abutments.

For strong ground motions of 0.6g and 0.8g PGA large passive deformations of the abutments are developed since the poundings occur due to the yield of the cables. The active deformations of the abutments increase a little comparing that for 0.4g PGA. When the ground motion intensity reaches 0.8g, the responses even with the cables are not desirable; the ductility reaches over 4.0, the opening is beyond 120mm, and the passive deformation gets to 45mm.

The results in Table 1 indicate that the cables improve the seismic responses of a MSC bridge slightly but are not effective to obtain a desirable result. The reason is that the cables are not strong enough to restrict the deck displacement. If more cables are used, the opening could be restricted. However, the active deformation of abutments due to large pulling forces of the cables could increase. Basically, a restrainer cable can not transfer larger force to an than

Table 1 Responses of as-built and retrofitted bridge by restrainer cables

PGA	Column ductility		Pier drift ratio(mm)		FBD(mm)	EBD(mm)			Opening(mm)		Abutment deformation(mm)			
	μ1	μ2	dr1	dr2	fb1	eb1	eb2	eb3	op1	op2	ab1+	ab1-	ab2+	ab1-
As-built bridge														
0.2	0.71	0.32	0.45	0.20	0.29	32.3	20.0	32.6	32.3	25.3	0.47	0.19	0.44	0.22
0.4	2.55	0.49	1.17	0.31	0.84	82.4	61.0	77.1	82.4	70.4	0.83	0.34	0.77	4.86
0.6	3.20	0.62	1.27	0.38	1.83	89.6	69.9	88.4	59.6	88.4	0.88	9.04	0.90	10.0
0.8	4.67	0.88	1.92	0.52	12.53	142.8	124.3	136.2	142.8	136.2	1.27	53.5	1.24	61.3
0.6	3.20	0.62	1.27	0.38	1.83	89.6	69.9	88.4	59.6	88.4	0.88	9.04	0.90	10.0
0.8	4.67	0.88	1.92	0.52	12.53	142.8	124.3	136.2	142.8	136.2	1.27	53.5	1.24	61.3
Retrofitted bridge by restrainer cables														
0.2	0.79	0.56	0.49	0.35	0.31	30.6	12.3	35.8	30.6	25.8	4.94	0.21	4.04	0.24
0.4	2.30	1.56	1.08	0.85	0.80	70.7	17.9	76.3	70.7	51.1	6.08	0.30	5.78	0.91
0.6	3.01	2.37	1.35	1.14	5.39	92.2	24.6	85.1	92.2	85.1	6.43	10.9	6.34	16.4
0.8	4.03	3.77	1.67	1.56	10.1	107.1	31.5	120.5	107.1	120.5	6.68	44.7	6.92	32.7

* FBD : Fixed Bearing Deformation
* EBD : Expansion Bearing Deformation

abutment its ultimate strength in active action. Therefore, the utilization of both capacity of an abutment in active and passive action could improve the seismic responses of the bridge more effectively.

6. Responses with shape memory alloy-restrainer-dampers

Two types of shape memory alloy-restrainer-dampers (SMA-RD) for abutments are introduced in this study. Type I is activated in active and passive action. In the case the ultimate capacity in active action is critical factor to design a SMA-RD since the capacity in active action is less than that in passive action. Type II functions only in passive action and, therefore, the critical factor is the capacity in passive action.

There are two parameters to design a SMA-RD. The first one is the yield force of a SMA wire that depends on the SMA property and the cross section area of a wire. The other one is the strain of a SIM hardening that relies on the length of a wire. As DesRoches[8] mentioned, the property can be useful to restraint openings.

In this study considering these two parameters, a parametric study for each SMA-RD will be conducted to understand how the bridge responses are affected by the variation of the parameters. The same El Centro ground motion scaled to 0.8g PGA is used for the parametric studies. In these parametric studies slacks of SMA-RDs are not included; the purpose of this parametric study is to determine which parameter is the most effective to protect the bridge.

Based on the results of the above parametric study, the most desirable design will be chosen. Then, the responses with the SMA-RD will be compared to those of the restrainer cables. For comparing, both cases of with and without the slack (6.35mm) of the SMA-RD will be analyzed.

6.1 SMA-RD for columns

A SMA-RD is designed for columns where expansion bearings are located. The SMA-RDs for columns have the same yield strength as that of lead-rubber bearings used in Choi's study.[1] Therefore, the yield strength of the device is 80kN. The length is 2.0m and thus the SIM hardening occurs after 122mm deformation. Fig. 12 shows an example for the hysteretic curves of the device. This device is activated in two ways such as Type I above. This SMA-RD for columns will be used for both parameter studies.

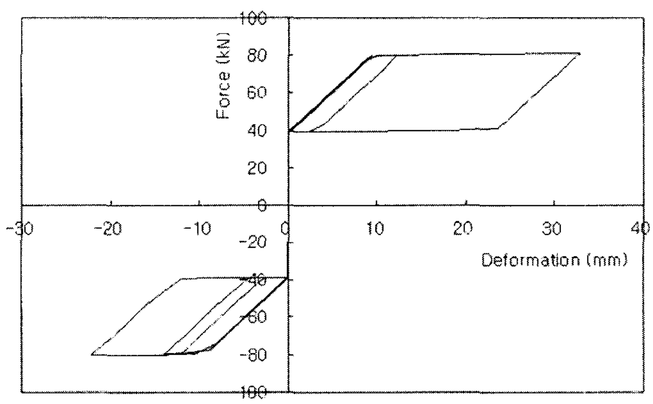


Fig. 12 Hysteretic curves of a SMA-RD for columns

6.2 Parametric study for Type I SMA-RD

The first parametric study considers that the yield forces of the SMA wire are equal to 1/4, 1/2, 3/4, and 4/4 of the ultimate capacity(3025kN) of an abutment in active action. The strain values of the SIM hardening are assumed to be 50, 64, 76, and 89mm. The gap size at the abutments is 76mm, thus the strain values are at first smaller than the gap and getting larger. There are four yield forces for a case of the strain of a SIM hardening.

The results of the parametric study are proposed in Table 2. The SIM hardening distance does not have a serious effect on the responses. However, the yield strength of the wire affects the responses significantly. The column ductilities and the openings decrease with increasing the yield strength. In abutments the active deformations increase but the passive deformations decrease with increasing the strength. When the yield strength of the SMA-RD is equal to the pulling ultimate capacity of the abutments, the passive abutment deformation is very small; which means a pounding does not occur.

In general, the responses with Type I SMA-RD for the 0.8g PGA are improved comparing with those for the restrainer cables. However, Type I produces a problem on the abutments for all cases. The ultimate deformations are 25mm and 35mm for active and passive action, respectively. The maximum active and passive deformations exceed the ultimate ones. In conclusion, the Type I SMA-RD is not adequate to obtain the satisfactory seismic resistance of the example bridge.

6.3 Parametric study for Type II SMA-RD

In this parametric study, the yield strengths of the wire are equal to 1/8, 1/4, 2/4, and 3/4 of the passive capacity of an abutment(15830kN) that is 5.24 times of that in active action. The results are proposed in Table 3. As expected, the active deformations of the abutments decrease sharply since only expansion bearings pull the abutments. The SIM hardening distance is not so influential. Viewing the maximum passive deformation of the abutments, the last one, which has the 3/4 strength of an abutment passive capacity, is satisfactory and the others get over or almost reach the ultimate passive abutment deformation (35mm). The three unsatisfactory cases do not have enough strength to restrict deck movement and thus the passive deformation become large due to pounding between the deck and the abutments. When the SMA wires have strong enough to prevent the pounding, all responses are improved significantly. In the case the maximum ductility(μ=1.11) is

Table 2 Results of a parametric study for Type I SMA-RD with 0.8g PGA ground motion

Type	Column ductility		Pier drift ratio(mm)		FBD(mm)		EBD(mm)		Opening(mm)		Abutment deformation(mm)			
	$\mu 1$	$\mu 2$	dr1	dr2	fb1	eb1	eb2	eb3	op1	op2	ab1+	ab1−	ab2+	ab1−
SIM hardening occurs at the deformation of 50mm														
1/4	3.85	3.55	1.73	1.48	8.95	92.1	31.3	106.1	92.1	106.1	14.3	49.2	24.3	24.8
2/4	4.33	3.33	1.85	1.54	7.11	78.5	29.2	77.9	69.2	71.0	28.5	55.5	66.0	16.2
3/4	3.45	2.83	1.61	1.36	4.78	78.0	22.0	63.4	51.8	56.6	17.9	37.4	61.5	6.3
4/4	2.20	2.09	1.07	1.03	1.10	62.1	5.6	66.3	15.1	12.1	60.9	8.0	58.4	9.0
SIM hardening occurs at the deformation of 64mm														
1/4	3.68	3.56	1.68	1.48	9.08	97.6	30.3	108.8	97.6	108.8	9.8	45.9	18.0	25.6
2/4	4.28	3.35	1.83	1.51	7.71	78.7	30.9	82.4	78.3	82.4	21.7	54.8	54.4	18.7
3/4	3.47	2.79	1.61	1.35	5.55	78.2	23.9	68.4	55.0	68.4	16.3	38.4	50.5	4.9
4/4	2.26	2.09	1.09	1.03	1.12	65.4	5.9	69.6	15.8	12.4	61.9	6.0	58.8	7.0
SIM hardening occurs at the deformation of 76mm														
1/4	3.61	3.55	1.66	1.47	8.80	102.4	30.1	112.8	102.4	112.8	7.1	44.0	12.4	27.7
2/4	4.23	3.38	1.82	1.49	7.96	85.8	31.5	93.9	85.8	93.9	15.4	54.3	42.4	20.0
3/4	3.49	2.75	1.62	1.35	5.96	78.5	24.6	80.2	56.0	80.2	16.4	39.1	39.5	4.3
4/4	2.28	2.11	1.09	1.03	1.17	66.0	5.9	71.6	16.0	12.4	62.1	5.6	58.8	5.7
SIM hardening occurs at the deformation of 89mm														
1/4	3.57	3.53	1.64	1.45	8.73	104.8	30.6	117.0	104.8	117.0	5.9	42.9	7.5	28.8
2/4	4.22	3.30	1.82	1.49	8.37	93.0	31.6	105.4	93.0	105.4	8.7	54.5	30.9	20.4
3/4	3.49	2.75	1.62	1.35	6.12	78.6	24.8	92.0	56.0	92.0	16.4	39.4	27.9	4.3
4/4	2.28	2.11	1.09	1.03	1.17	66.0	5.9	71.6	16.0	12.4	62.1	5.6	58.8	5.7

Table 3 Results of a parametric study for Type II SMA-RD with 0.8g PGA ground motion

Type	Column ductility		Pier drift ratio(mm)		FBD(mm)		EBD(mm)		Opening(mm)		Abutment deformation(mm)			
	μ1	μ2	dr1	dr2	fb1	eb1	eb2	eb3	op1	op2	ab1+	ab1-	ab2+	ab1-
SIM hardening occurs at the deformation of 50 mm														
1/8	3.69	3.73	1.65	1.53	9.34	112.1	32.7	125.7	112.1	125.7	1.1	44.1	1.2	31.2
1/4	4.33	3.25	1.85	1.50	9.51	101.8	36.6	140.6	101.8	140.6	1.0	58.5	1.3	21.0
2/4	3.02	2.65	1.47	1.32	3.58	77.1	15.6	108.8	77.1	108.8	0.8	34.0	1.1	13.5
3/4	1.11	1.05	0.62	0.60	3.8	45.7	3.5	38.7	45.7	38.7	0.6	14.1	0.5	14.2
SIM hardening occurs at the deformation of 64 mm														
1/8	3.62	3.71	1.60	1.50	8.83	111.5	31.7	121.8	111.5	121.8	1.0	40.6	1.1	31.0
1/4	4.14	3.32	1.81	1.46	8.78	108.4	33.7	134.7	108.4	134.7	1.0	53.8	1.2	27.2
2/4	3.20	2.66	1.53	1.33	5.74	77.6	20.8	114.1	77.2	114.1	0.8	32.7	1.1	10.0
3/4	1.11	1.05	0.62	0.60	3.38	45.7	3.5	38.7	45.7	38.7	0.6	14.1	0.5	14.2
SIM hardening occurs at the deformation of 76 mm														
1/8	3.61	3.69	1.59	1.49	8.80	112.1	32.0	121.2	112.1	121.2	1.1	39.6	1.1	31.6
1/4	4.14	3.32	1.81	1.46	8.78	108.4	33.7	134.7	108.4	134.7	1.0	53.8	1.2	27.2
2/4	3.20	2.66	1.53	1.33	5.74	77.6	20.8	114.1	77.2	114.1	0.8	32.7	1.1	10.0
3/4	1.11	1.05	0.62	0.60	3.38	45.7	3.5	38.7	45.7	38.7	0.6	14.1	0.5	14.2
SIM hardening occurs at the deformation of 89 mm														
1/8	3.61	3.69	1.59	1.49	8.80	112.1	32.0	121.2	112.1	121.2	1.1	39.6	1.1	31.6
1/4	4.14	3.32	1.81	1.46	8.78	108.4	33.7	134.7	108.4	134.7	1.0	53.8	1.2	27.2
2/4	3.20	2.66	1.53	1.33	5.74	77.6	20.8	114.1	77.2	114.1	0.8	32.7	1.1	10.0
3/4	1.11	1.05	0.62	0.60	3.38	45.7	3.5	38.7	45.7	38.7	0.6	14.1	0.5	14.2

about a quarter of that with the restrainer cables and the maximum opening(45.7mm) is just 38% of the counter value for the cables. The maximum passive deformation of the abutments is 14.1mm that is less than the first yield deformation(14.6mm) shown in Fig. 6, thus the abutments remain in elastic range.

Three quarters of the passive abutment capacity is 8340kN, and thus 1042.5kN is required for each girder. From Fig, 5, the estimated wire's area is 1969mm^2 and 4 wires having the diameter of 18mm are needed.

6.4 Comparing results of restrainer cables and SMA-RDs

From the parametric studies the best SMA-RD is chosen for the analyses with weak and strong ground motions; the best one is the Type II with the yield force of 3/4 the ultimate capacity of the abutment. Here, the SMA-RD with a slack of 6.35mm as well as without the slack, both are considered. The results of the three devices are illustrated in Fig. 13; where 1) the ductility of P1 column, 2) the opening on A1 abutment, and 3) the active and passive deformation of A1 abutment are proposed.

The ductility with the restrainer cables reaches 2.3 by the 0.4g PGA ground motion, thus the columns are damaged with moderate ground motions. However, the SMA-RD bridges have the ductility of 1.1 and 2.1 without and with the slack, respectively, by the 0.8g PGA ground motion. Therefore, the demand on the column decrease sharply by the SMA-RDs.

The ductility with the restrainer cables increase abruptly at the PGA of 0.4g since the cables are yielded; this can be recognized by observing that the opening also increase enormously at the 0.4g PGA and the active deformation of the abutment is almost same after the 0.4g PGA.

The passive abutment deformations with the restrainer cables are very small for 0.2g and 0.4g PGA. However, the values become large for 0.6g and 0.8g PGA due to pounding at the abutments since the cables yield. On the contrary, the SMA-RDs, at first, produce large passive abutment deformations relatively for 0.2g and 0.4g PGA, but limit the passive deformation within 14.7mm even for the strongest ground motion of 0.8g PGA. The SMA-RDs restraint the deck movement effectively and improve all responses comparing to those for the restrainer cables.

7. Conclusions

This study showed that the as-built MSC bridge is vulnerable to seismic loads, and the restrainer cables conventionally used in California of the United States did not

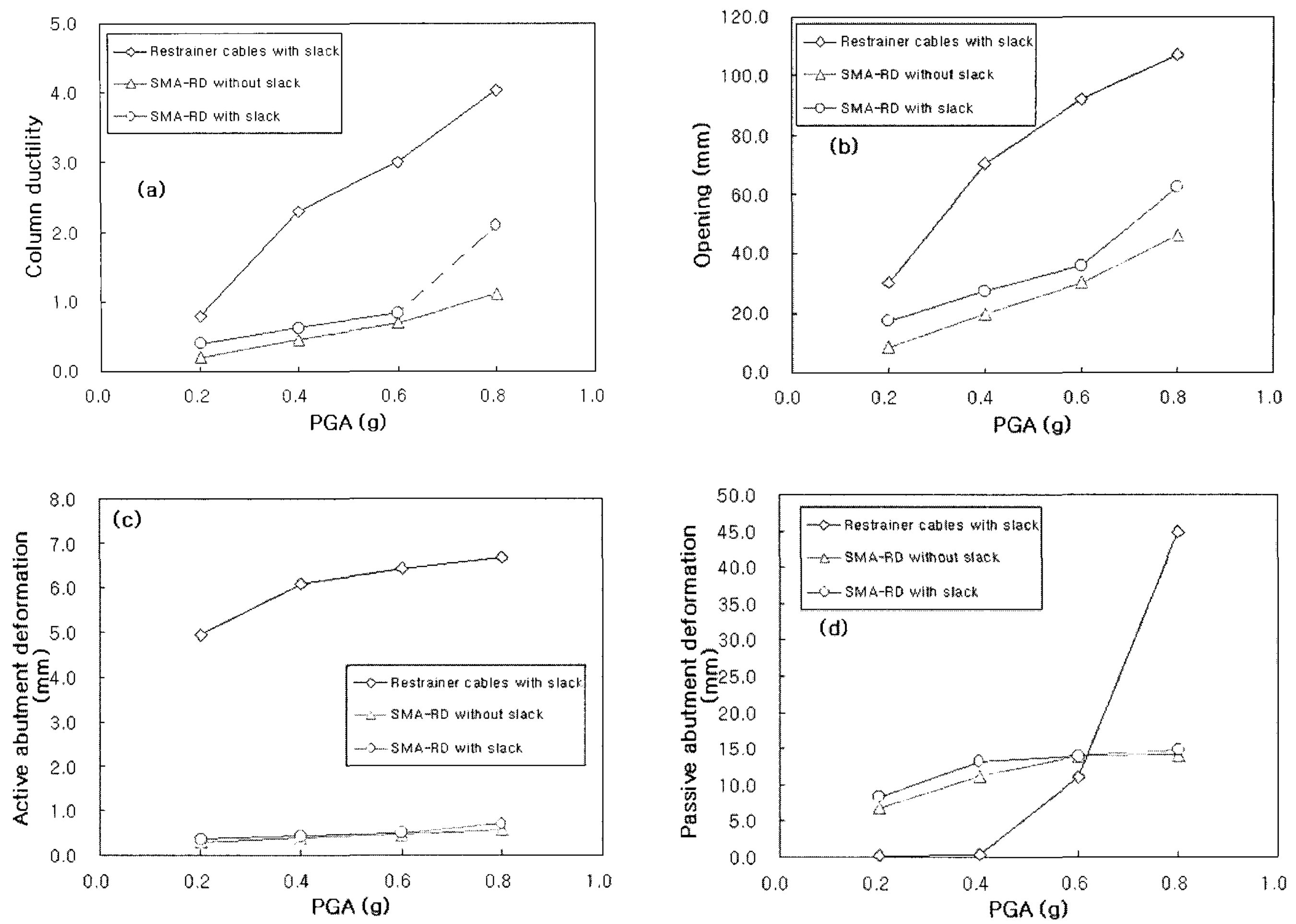


Fig. 13 Comparing results of the bridge retrofitted by restrainer cables or SMA-RDs

improve the vulnerability. Even for a moderate ground motion of 0.4g PGA, the bridge with the cables was damaged on the column.

Therefore, this study proposed a new device using shape memory ally wires to restrict deck movements and protect bridge's components from seismic loads. The device unlike a restrainer cable can use the capacity of abutments in pulling and pushing direction(two-way) or pushing(one-way) only. This study proposed two types of the device that were investigated the performance through two parametric studies. The parametric studies indicated that the two-way device working in pulling and pushing direction is not effective to improve the seismic resistance of the bridge, but the one-way device working in pushing direction can be effective with strong shape memory alloy wires.

When the device was installed in the bridge, it was safe from the 0.6g PGA ground motion and the results for the 0.8g PGA is satisfactory although the column ductility reaches 2.1. Consequently, the proposed shape memory alloy-restrainer-damper can be an alternative to protect multiple span continuous steel bridges in the central and southeastern of United States.

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