NEW STRUCTURE OF PIERS OF RIGID FRAME BRIDGE USING SEISMIC RESPONSE CONTROL DEVICE

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Abstract

A seismic response control method that applies damping devices to piers of rigid frame bridge is proposed. Longer natural period due to the replacement of a pier with four slender concrete columns and damping devices between them results in reduction of response acceleration. In this method, since seismic control devices are incorporated in longitudinal and transverse direction, response control can be expected in both directions. A reduction of construction costs can be expected by application of control devices because it is possible to reduce the amount of concrete and rebar in pier, make foundation scale small and decrease earthquake-proof reinforcement of superstructure. In this paper, the outline of proposed seismic response control structure and results of examination of structural feasibility and seismic safety are reported.

Introduction

Securing structural safety for strong earthquake is indispensable in the design of the bridge based on the specifications after Kobe Earthquake. One of alternatives for this demand is to mitigate seismic force by applying seismic isolation bearings. However, bearings are not always advantageous in terms of maintenance and the cost. Consequently the continuous rigid frame bridges are often adopted. This paper reports a study on the structure that can absorb earthquake energy with long natural period by making the pier slender and with application of dampers.

Proposed Seismic Response Control Bridge

Proposed seismic response control bridge (Control Bridge) has plural reinforced concrete columns which are connected with steel truss. Control devices are incorporated so that they can absorb earthquake energy through their relative displacement in vertical direction (Fig.1). The steel dampers (Photograph.1) are used as control devices. They are steel dampers which are superior in durability and reliability. Control devices are installed from the bottom to the top of the pier.

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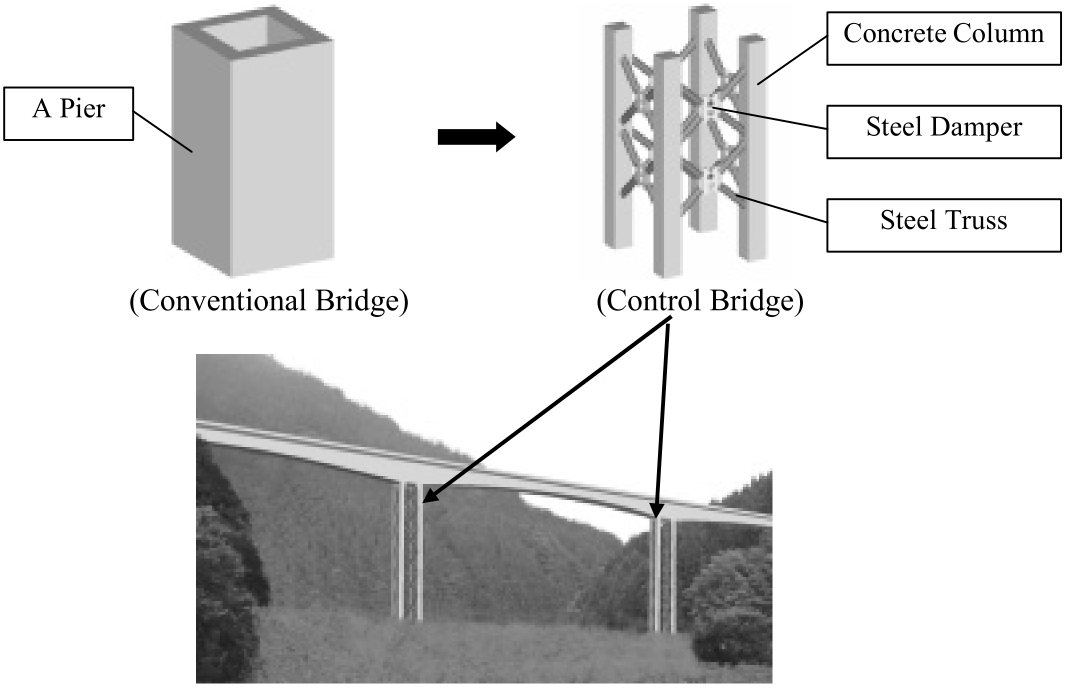


Fig.1 Concept of Seismic Response Control Bridge

Photo.1 Steel Damper

Feature of the Seismic Response Control Bridge

Features of Control Bridge are shown below.

(1) Absorption of earthquake energy

Steel Damper absorbs earthquake energy by virtue of a plastic deformation of steel that has a low yield stress (Table.1). Since this bridge incorporates dampers in both longitudinal and transverse directions, the structure can control seismic force in both directions.

Table.1 Mechanical Property of Steel used for Damper

Lower Yield Stress (N/mm^2)	Tensile Strength (N/mm^2)	Total Elongation (%)
215-245	below 400	no less than 40

(2) Decrease of the response acceleration due to change in natural period

It is recognized that casualties in earthquake would be more serious when natural period of structure coincides with peak period of the earthquake motion. It is effective to let natural period longer and avoid the coincidence of the period in order to secure seismic safety. Response acceleration during earthquake will be greatly decreased in Control Bridge because pier structure is not rigid.

(3) Reduction of an execution cost and simplification of maintenance

A reduction of construction costs can be expected by application of control devices because it is possible to reduce the amount of concrete and rebar in pier, make foundation scale small and decrease earthquake-proof reinforcement of superstructure of a concrete. Furthermore, a steel damper is comparatively reasonable material, and can keep its initial mechanical property after six times of huge earthquakes. Thus, restoration cost for casualty in earthquake is reasonable as compared to conventional bridge.

Investigation on the feasibility and seismic safety

(1) Purpose of the investigation

Feasibility and seismic safety of Control Bridge are examined in a series of bridge structural design in this chapter.

(2) Method of the investigation

Conventional prestressed concrete 3-span continuous rigid frame bridge is investigated in this study. Replacing pier with control bridge structure shown in Fig.1 is examined. In order to confirm feasibility of the control bridge structure, serviceability of the bridge is investigated considering change in structure from erection period to completion and influence of creep and shrinkage, and seismic safety is investigated for big earthquake. In addition, seismic control effect is investigated by comparing results of earthquake response analyses for conventional bridge and Control Bridge.

(3) Condition of the investigation

(a) Example bridge for investigation

Conventional bridge, used as an example bridge of investigation, is shown in Fig.2.

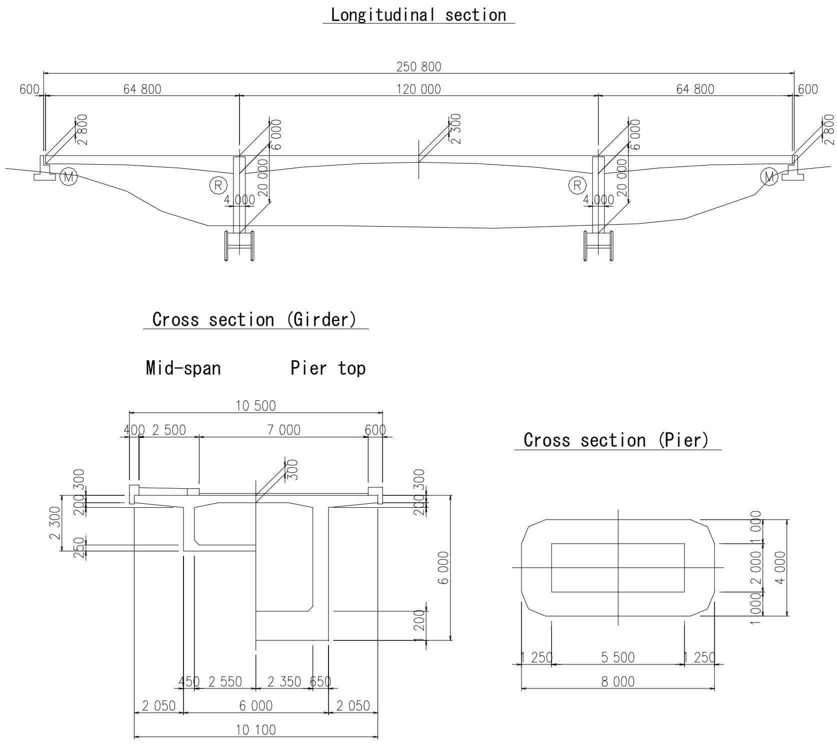
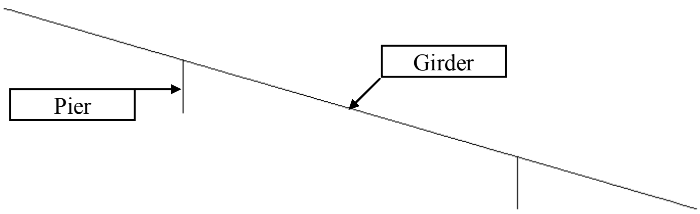


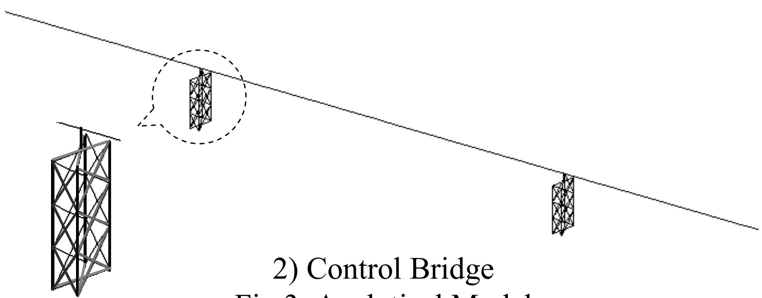
Fig.2 General View of Example Bridge

(b) Analytical model

Fig. 3 shows the analytical model. It is a whole bridge model and is the 3-D frame model with mass on each node. As for boundary condition, horizontal roller is applied at the end of the girder and soil spring elements are applied at the bottom of piers.



1) Conventional Bridge



2) Control Bridge

Fig.3 Analytical Model

(c) Material property

Table.2 shows the material property. Since compressive stress of concrete in pier of the control bridge is big, high strength concrete is necessary and then high strength rebar is applied for the pier.

Table.2 Material Property

Material	Member	Strength, Type	
		Control Bridge	Conventional Bridge
Concrete	Pier	f'_{ck}=70N/mm^2	f'_{ck}=24N/mm^2
	Girder	f'_{ck}=40N/mm^2	f'_{ck}=40N/mm^2
Reinforcing Bar	Pier	SD490	SD345
Steel Truss	Pier	STK400, φ=300mm, t=16mm	—
Steel Damper	Pier	TypeL, 3 teeth	—
Prestressing Cable	Girder	SWPR7B 12S12.7	SWPR7B 12S12.7

(d) Nonlinear property of reinforced concrete

Pier members are modeled as nonlinear beam elements because reinforced concrete of pier is expected to be plastic during earthquake in nonlinear dynamic analysis. A skeleton curve of this nonlinear element is modeled as a tri-linear curve which considers crack in concrete, yielding of reinforcing bar. Takeda model is used for hysteresis model and kinematic hardening model is used for hardening. Reinforced concrete section of pier in Control Bridge is shown in Fig.4.

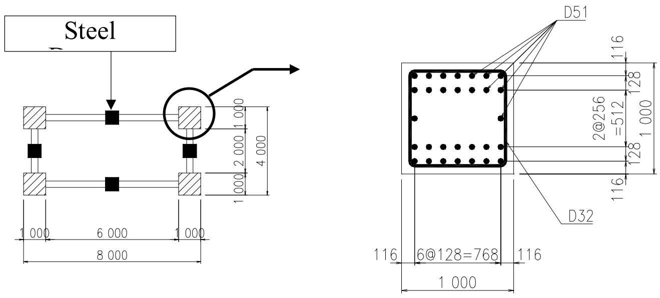
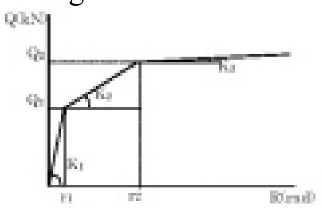


Fig.4 Reinforced Concrete Section of Pier (Control Bridge)

(e) Modeling of the steel damper

Force-deformation in shear of steel damper is modeled by tri-linear skeleton curve. Kinematic hardening model is used for hardening. Elasto-plastic property of steel damper is shown in Fig.5.



K_1	(kN/mm)	176.4
K_2	(kN/mm)	17.6
K_3	(kN/mm)	0.9
Q_1	(kN)	114.9
Q_2	(kN)	183.6

Fig.5 Elasto-plastic Property of Steel Damper

(f) Input earthquake motion

Level2-Type2 earthquake motion shown in “Specifications for highway bridges partV; seismic design”[2] is used as an input earthquake motion. Time-history of acceleration is shown in Fig.6.

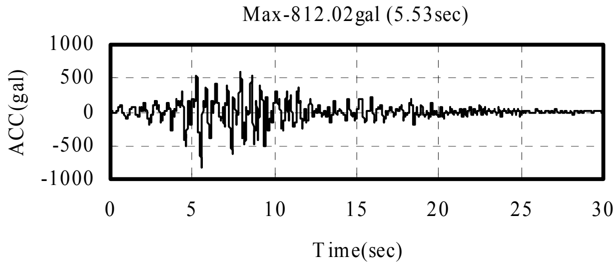


Fig.6 Acceleration Time-history of Input Earthquake Motion

(g) Damping Coefficient

Equivalent damping coefficient set for each structural element based on “Specifications for highway bridges partV; seismic design”[2] is shown in table -3. Rayleigh damping coefficient calculated by mode damping is used in dynamic analysis.

Table.3 Equivalent Damping Coefficient

Element	Damping Coefficient
Superstructure	0.03
Pier(RC)	0.02
Damper	0.00
Rigid Member	0.00
Steel Pipe	0.04
Soil Spring	0.30

(4) Results of investigation

(a) Results of investigation for feasibility

1) Reinforced concrete column

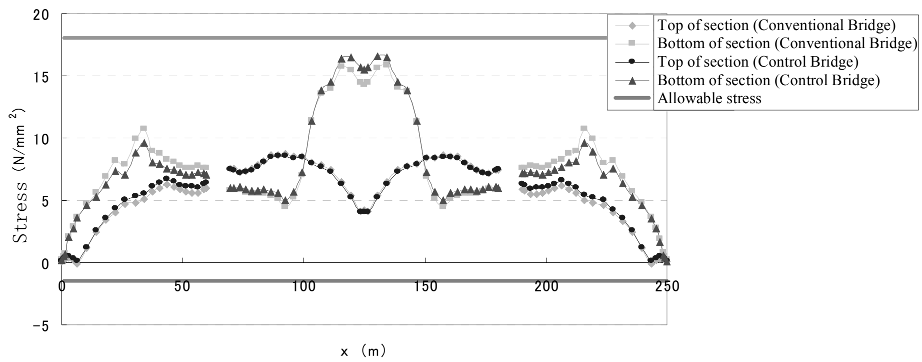
It is confirmed that stresses at service load are within allowable stress. Structural safety of reinforced concrete column for flexure and shear is confirmed by checking sectional forces during big earthquake if they are within strength of section. Stresses of concrete and reinforcing bar at service load and allowable stresses are shown in Table.4.

Table.4 Stresses of Concrete and Reinforcing Bar at Service Load

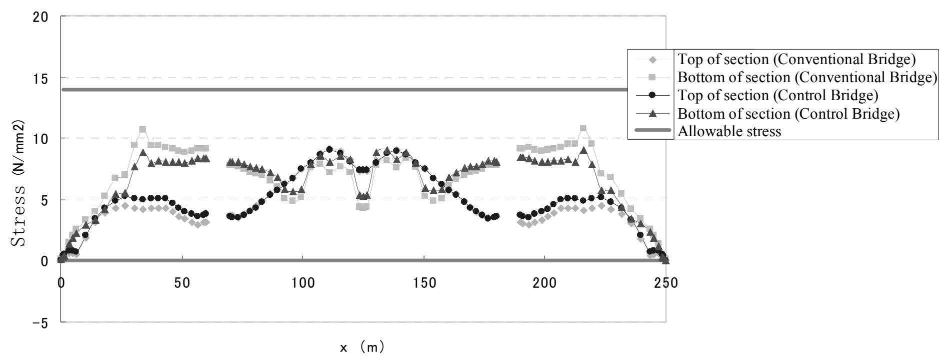
Load			Stress at the bottom of pier(N/mm^2)		Allowable Stress (N/mm^2)
			Left	Right	
Dead Load	Concrete	Compression	13	16	20
	Rebar	Tensile	42	37	100
		Compression	147	191	250
Live Load M_{max}	Concrete	Compression	15	17	20
	Rebar	Tensile	45	82	180
		Compression	179	200	250

2) Main girder

It is verified that stresses of main girder at service load are within allowable stress and structural behavior during big earthquake is within elastic range. Bending stresses of concrete in main girder are shown in Fig.7.



a) At the Time Service is Started



b) At the Time Creep Deformations Finished

Fig.7 Stresses of Concrete in Main Girder

3) Steel truss

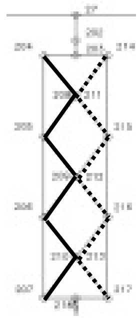
The followings are confirmed based on “Specifications for highway bridges partII;

steel bridge”[1].

a) Structural safety check of the steel pipe member under bending and axial force

b) Structural safety check of the steel pipe member under axial and shear force

Flexural safety of steel truss at live load is confirmed as shown in Fig.8.



Member		Axial Force (kN)		Bending Moment (kN·m)		Stress (N/mm^2)		Allowable Stress (N/mm^2)
Node-I	Node-J	Node-I	Node-J	Node-I	Node-J	Node-I	Node-J	
204	208	262	882	-58	-20	-21	21	140
208	205	121	-1,492	32	15	21	-45	140
205	209	195	2,702	27	40	21	116	140
209	206	32	-1,521	-22	-9	-10	-58	140
206	210	391	1,623	123	84	78	100	140
210	207	258	-858	-44	-26	-14	-43	140
214	211	262	-853	-94	-53	-40	-57	140
211	215	385	1,523	78	48	54	78	140
215	212	10	-2,670	-46	6	-24	-90	140
212	216	182	1,570	45	27	30	69	140
216	213	131	-1,590	74	48	43	-30	140
213	217	283	900	4	11	12	37	140

Fig.8 Stress Check in Steel Truss

4) Steel damper

Structural safety of steel dampers is evaluated by calculating Miner’s fatigue damage ratio (D). Results of calculation of the ratio for top, middle and bottom steel dampers are shown in Table.5. Safety of dampers are confirmed by assuring 1/D are bigger than 2.

Table.5 Fatigue Damage Ratio of Steel Dampers

Steel Damper	Fatigue Damage Ratio(D)	1/D
Top	0.135	7.43
Middle	0.355	2.81
Bottom	0.132	7.55

(b) Results of investigation for seismic safety

Comparison between conventional bridge and Control Bridge is shown in Table.6.

1) Response acceleration

Maximum horizontal response acceleration at mid-span is 975.48gal in conventional bridge and 159.40gal in Control Bridge. Control Bridge shows remarkable decrease in acceleration due to its longer natural period.

Table.6 Comparison of the Result of Analyses

<table>
<tr><th></th><th>Control Bridge</th><th>Conventional Bridge</th></tr>
<tr><td>Natural Period</td><td>T_1=1.114sec
</td><td>T_1=0.844sec
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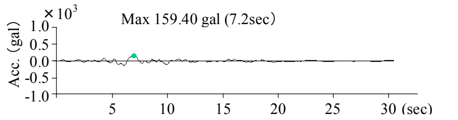
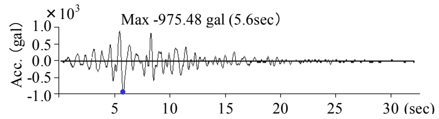
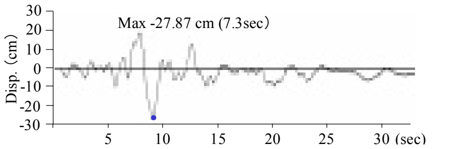
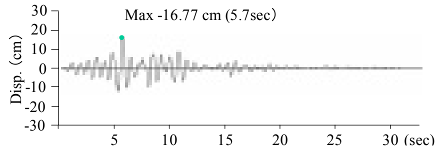
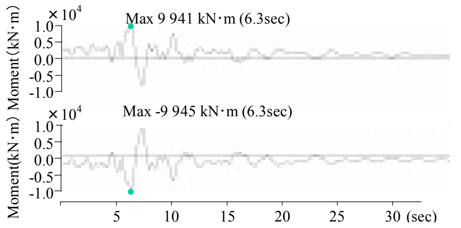
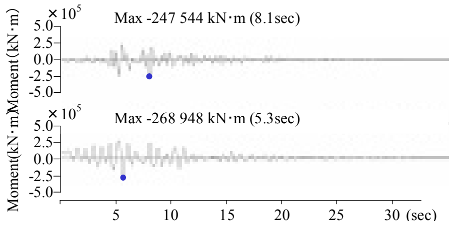
<tr><td>Response Acceleration

Mid-span</td><td></td><td></td></tr>
<tr><td>Response Displacement

Mid-span</td><td></td><td></td></tr>
<tr><td>Time-history and hysteretic loop of bending moment in plastic hinge</td><td></td><td></td></tr>
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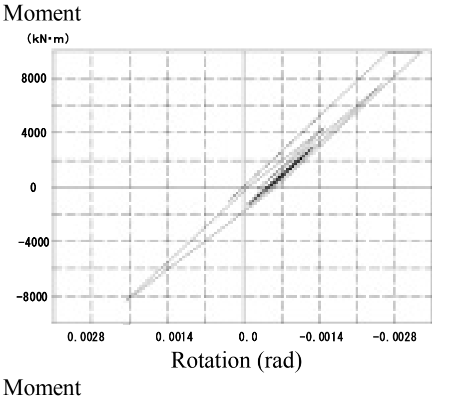
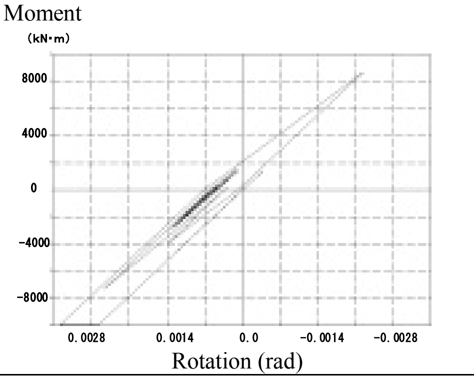
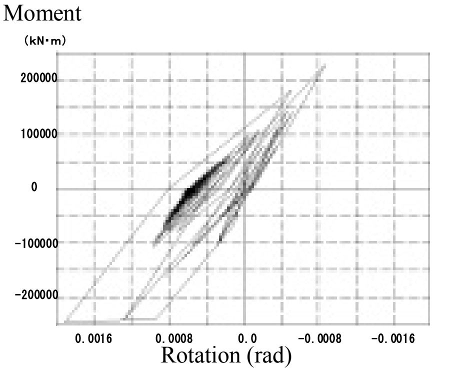
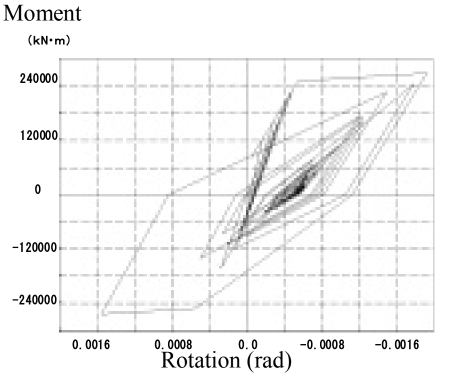
Top of pier

(Below)

Bottom of pier</td><td>
</td><td>
</td></tr>
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2) Response displacement

Maximum horizontal response displacement at mid-span is 16.77cm in conventional bridge and 27.87cm in Control Bridge. Displacement in Control Bridge is greater than conventional bridge, but it is less than displacement that may result in structural failure during earthquake.

3) Response bending moment at plastic hinge

Maximum bending moments at top and bottom plastic hinge are 247544kNm, 268948kNm in conventional bridge and 9941kNm, 9945kNm in Control Bridge. Bending moment is greatly decreased in Control Bridge.

4) Response history of plastic hinge

Larger plasticity is observed in conventional bridge than Control Bridge. As a result, energy absorption at plastic hinge is larger in conventional bridge. Since high-strength concrete is used in Control Bridge due to compressive stress in concrete at dead load, earthquake energy is absorbed not at plastic hinge but at steel damper.

Conclusion

In this paper, a seismic response control method that applies steel dampers to piers of rigid frame bridge was proposed. Feasibility and seismic safety of proposed seismic response control bridge structure were confirmed for prestressed concrete continuous rigid frame bridge whose maximum span is 120m and pier height is approximately 20m. Feasibility of proposed seismic response control bridge was verified through a series of bridge structural design procedure. Seismic safety of proposed bridge was examined in dynamic analysis so that damping effect of steel damper can be reflected in results. Remarkable decrease in response acceleration and resulting decrease in sectional force were observed. A reduction of construction costs can be expected by application of this method because it is possible to reduce the amount of concrete and rebar in pier, make foundation scale small and decrease earthquake-proof reinforcement of superstructure.

References

[1] Japan Road Association: Design Specifications for Highway Bridges partII; Steel Bridge, 2002.3

[2] Japan Road Association: Design Specifications for Highway Bridges partV; Seismic Design, 2002.3