SEISMIC DESIGN OF ARCH BRIDGES DURING STRONG EARTHQUAKE

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SUMMARY

In structural design of arch bridges, it is essential to determine plastic regions generated during strong earthquakes and to consider the effect of axial force fluctuation in dynamic response analysis.

In this study, nonlinear time history analysis is performed with respect to bridge's axis and transversal axis where the bridge is modeled as two-dimensional frame model. Three long periodic and three short periodic acceleration waves of approximately 3.30 m/sec2 and 6.30 m/sec2 maximum, respectively, are considered as seismic loads. The natural period in the bridge axis and transversal axis directions are found to be 1.47 sec and 1.17 sec, respectively, which implies that long periodic earthquakes are expected to produce more hazardous response.

Plastic regions generate at the upper end of fixed pier and end posts as well as at the base of arch ring when seismic force acts in bridge axis. In the transversal axis, plastic regions occur at the base of pier, end posts and arch ring where its area of generation is wider than in the bridge direction. Also, since natural period in the transversal direction is little short, plastic regions are produced even in short periodic earthquakes but safety of the bridge is still ensured since the ductility factor obtained is less than three.

Comparing the results of the case where axial force fluctuation is considered with the case where it is neglected, curvature at the base of arch ring increases by 20 percent and sectional force at the base of pier by 10 percent.

INTRODUCTION

The bridge considered in this study is a concrete deck Langer arch bridge with prestressed stiffening girders. It is 300 meters long with 143-meter arch span, which will be constructed over the Takachiho ravine, one of Japan's quasi-national park. Its main conditions considered in design are as follows:

1. The bridge must have a span of approximately 140 meters in order to cross Takachiho ravine;
2. Aesthetic form of the bridge is important since it will stand on a quasi-national park; and
3. Economical value of the bridge.

Different types of bridges that satisfy the above conditions were compared and evaluated. Overall evaluation result shows that reinforced concrete Langer arch bridge with prestressed stiffening girders is the most appropriate structure.

Seismic design of this bridge for strong earthquakes is performed by nonlinear dynamic analysis. The method of analysis and computed results along bridge axis is presented in this paper.

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SUMMARY OF BRIDGE

a) Type of bridge: Reinforced concrete Langer arch bridge with prestressed stiffening girders
b) Bridge length: *L*=300 meters
c) Span: *l* = 2@40 m + 150 m + 2@35 m
d) Arch span: 143 meters
e) Road width: *W*=15.5 meters
f) Cross section: refer to Fig. 1
g) General view of bridge: refer to Fig. 2

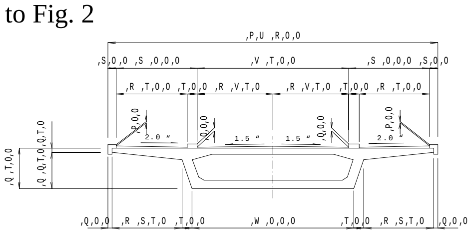

Figure1: Cross section of box girder

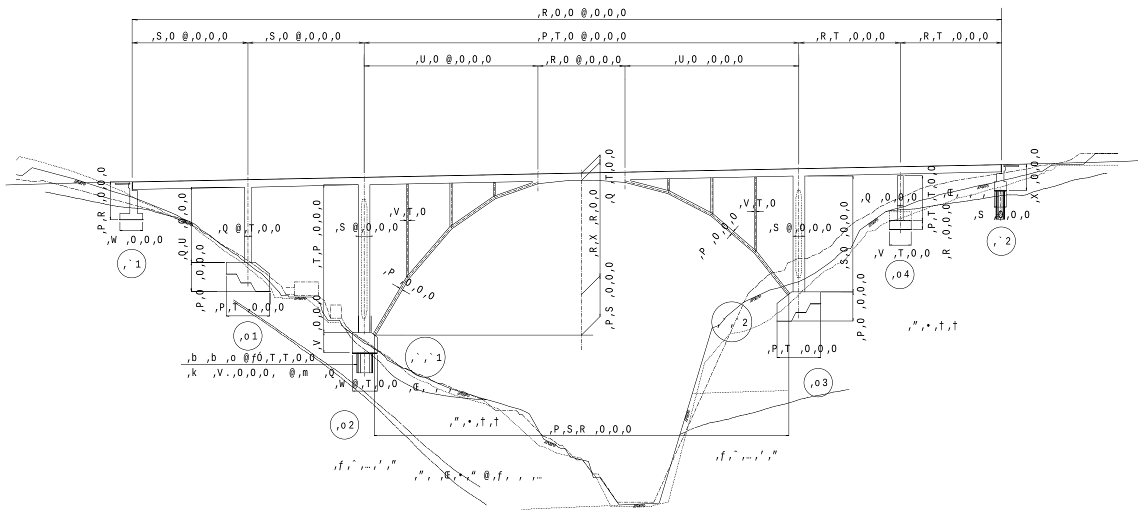

Figure2: Side view of bridge

METHOD OF ANALYSIS

Arch bridges, according to Design Specifications for Highway Bridges-Part V Seismic Design (1996) [1], are considered as structures that exhibit complex behaviour during strong earthquakes. Moreover, since it also statically indeterminate structures of high degree, nonlinear structural members are expected to generate in more than one area. This suggests that, in this case, energy constant rule is not valid and ductility design method is inapplicable. Therefore, dynamic response analysis should be carried out, where plastic hinge can be determined. Since the bridge is statically indeterminate, axial force acting on arch ring, vertical members and piers fluctuate due to horizontal action of earthquake. Effect of axial force fluctuation suggests changing of flexural moment and curvature relationship in the analysis. In this study, the effect of axial force fluctuation is investigated by comparing response curvature when axial force is maximum and minimum with allowable curvature. Here, relationship of flexural moment and curvature is varied in structural members found to yield when flexural strength due to dead load is considered.

There are two types of ground motions used in the analysis as indicated in Design Specifications of Highway Bridges-Part V Seismic Design (1996) [1], that is, Type I and Type II. Type I corresponds to plate boundary type large-scale earthquakes, which characterized by long periodic waves. On the other hand, Type II corresponds to inland direct strike type earthquake like the 1995 Hyogo-ken Nanbu Earthquake, which characterized by short periodic waves. Also, both are ground motions with high intensity, though less probable to occur during the service period of the bridge. Acceleration spectra for strong grounds (i.e. classified as ground Type I in Design

Specification of Highway Bridges), acceleration spectra ranges from 2.0 to 7.0 m/sec^2 in ground motion Type I and 0.75 to 200 m/sec^2 in Type II.

CONDITIONS FOR ANALYSIS
5.

a) Seismic classification of bridge: Class B (i.e. bridges considered with high importance)
b) Ground type: Type I (i.e. good diluvial ground and rock mass)
c) Regional classification: B class (areas with moderate probability of earthquake occurrence)
d) Frame model for dynamic analysis: refer to Fig. 3
   Nonlinear beam elements: piers (P1, P2, P3), vertical members (V1, V2), and arch ring
   Linear beam elements: pier (P4), vertical member (V2 to V5), stiffening girder

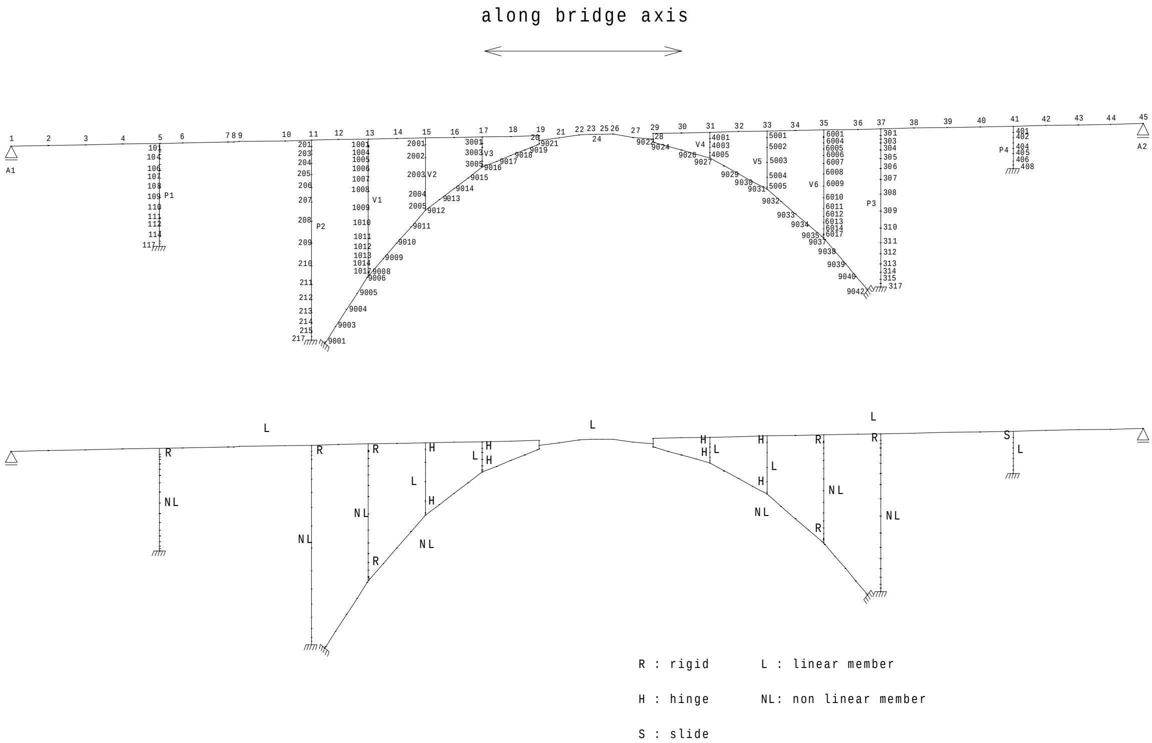

Figure 3: Frame model used in the analysis

e) Strength of structural members: refer to Table 1
f) Relationship of flexural moment and curvature for nonlinear structural members:
   Tri-linear degrading stiffness model (Takeda model) considering strength of reinforced concrete during cracking, yielding and ultimate stage.
g) Damping constants:
   Linear structural members: h = 0.05
   Nonlinear structural members: h = 0.0.2
   Strain energy types of modal damping constants are calculated using these values. Also, Rayleigh damping is considered for viscous damping in dynamic response analysis.
h) Direct integration:
   Method: Newmark-β method
   Time interval: 0.01/10 = 0.001 sec.
   Duration considered in the analysis: Total duration of input acceleration + 20 seconds of zero acceleration
i) Initial sectional force:
   Sectional forces due to dead load are considered in all structural members except in stiffening girders.
j) Direction of load:
   Only horizontal ground motion is considered. Also, considering the asymmetrical form of bridge, direction of input acceleration is considered in both sides along bridge axis.

Table 1: Strength of structural members

Structural		Concrete	Steel bars	Arrangement of reinforcement bars	notes
Superstructure	Stiffening	40 /mm^2	SD295		
	Arch ring	40 /mm^2	SD345	Main bars: D32ctc125(2.0steps),	
	Vertical member	30 /mm^2	SD345	Main bars: D32ctc125(1.0step),	V1, V6
		24 /mm^2	SD295		V2 to V5
Substructure	Pier P1	30 /mm^2	SD345	Main bars: D51ctc150(2.0steps),	
	Pier P2	21 /mm^2	SD295	Main bars: D38ctc125(1.0step),	
	Pier P3	21 /mm^2	SD295	Main bars: D51ctc150(1.0step),	
	Pier P4	21 /mm^2	SD295		

6. EIGEN ANALYSIS

Eigen analysis is used to examine the seismic characteristic and viscous damping property of bridge structure. Results are shown in Table 2 and Fig. 4. As indicated in these results, first and eighth vibration modes are found to be dominant.

Table 2: Eigen Analytic Results

degree of mode	natural frequency	natural period	participation factor		effective mass		modal damping constant
i	(Hz)	(sec)	along bridge axis	vertical direction	along bridge axis	vertical direction	h_i
1	0.67875	1.47330	36.960	1.684	61	0	0.04562
2	1.42730	0.70062	1.031	-1.091	61	0	0.04980
3	2.21750	0.45097	5.129	-0.935	62	0	0.04958
4	2.65970	0.37598	-2.053	1.191	62	0	0.04911
5	3.18250	0.31422	3.455	-11.270	63	6	0.04980
6	3.80090	0.26309	-11.470	-1.160	68	6	0.04962
7	3.89090	0.25701	7.296	11.030	71	12	0.04928
8	4.02010	0.24875	13.680	-8.235	79	15	0.04861
9	4.15180	0.24086	5.642	0.087	80	15	0.04803
10	4.28090	0.23359	0.874	-13.680	80	23	0.04965
11	4.32830	0.23104	2.369	-0.036	81	23	0.04971
12	4.36750	0.22897	1.284	-2.341	81	23	0.04954
13	4.62890	0.21604	3.630	5.212	81	25	0.04966
14	4.88160	0.20485	-3.858	2.836	82	25	0.04979
15	5.08170	0.19678	3.308	-15.860	83	36	0.04956
16	5.21930	0.19160	-2.183	-8.089	83	39	0.04957
17	6.00220	0.16660	-5.030	-6.442	84	41	0.04985
18	6.19790	0.16135	-1.672	0.002	84	41	0.04856
19	6.35040	0.15747	0.718	5.527	84	43	0.04987
20	6.74180	0.14833	2.240	13.510	84	51	0.04910

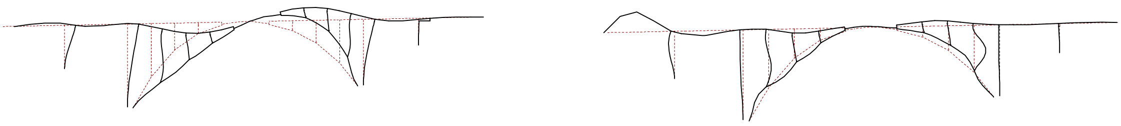

Figure 4: Dominant vibration modes

DYNAMIC RESPONSE ANALYSIS WITHOUT AXIAL FORCE FLUCTUATION EFFECT

Nonlinear dynamic response analysis is conducted using flexural moment and curvature relationships of members due to axial force acted by dead load. Results are shown in Fig. 5 to Fig. 10. It is revealed in these graphs that response curvatures are within allowable values.

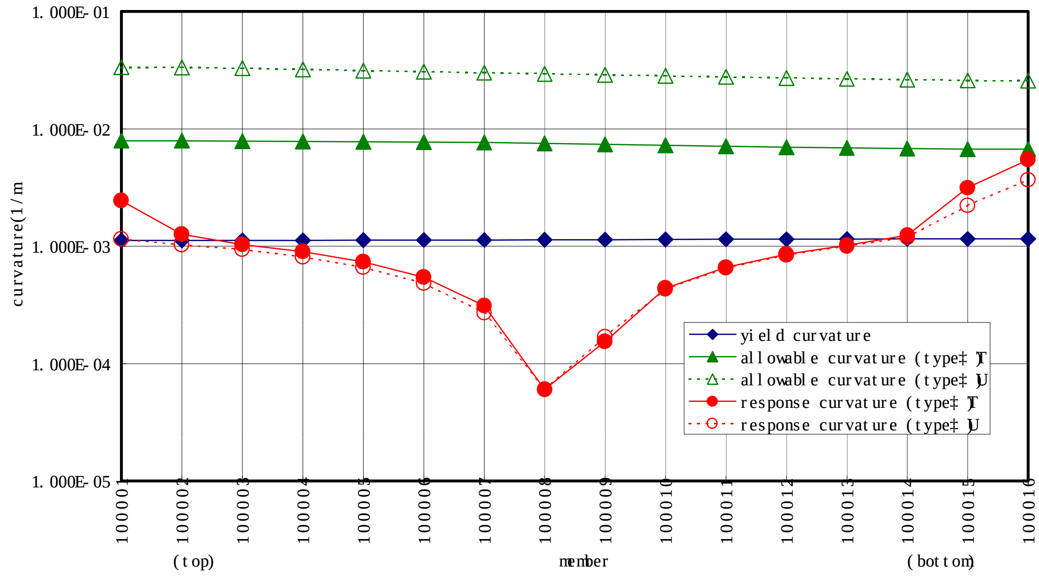

Figure 5: Response curvature and allowable curvature of pier P1

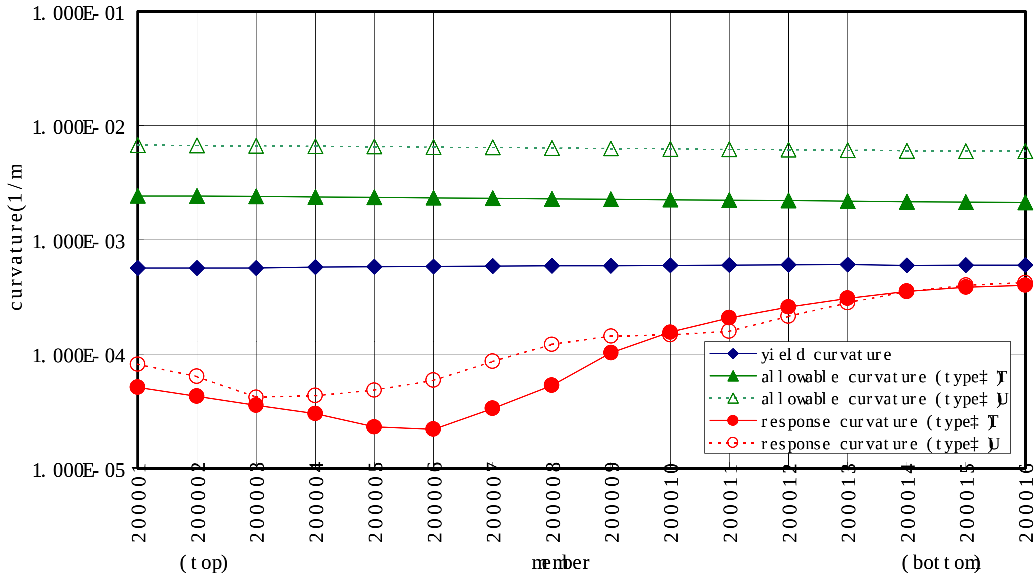

Figure 6: Response curvature and allowable curvature of pier P2

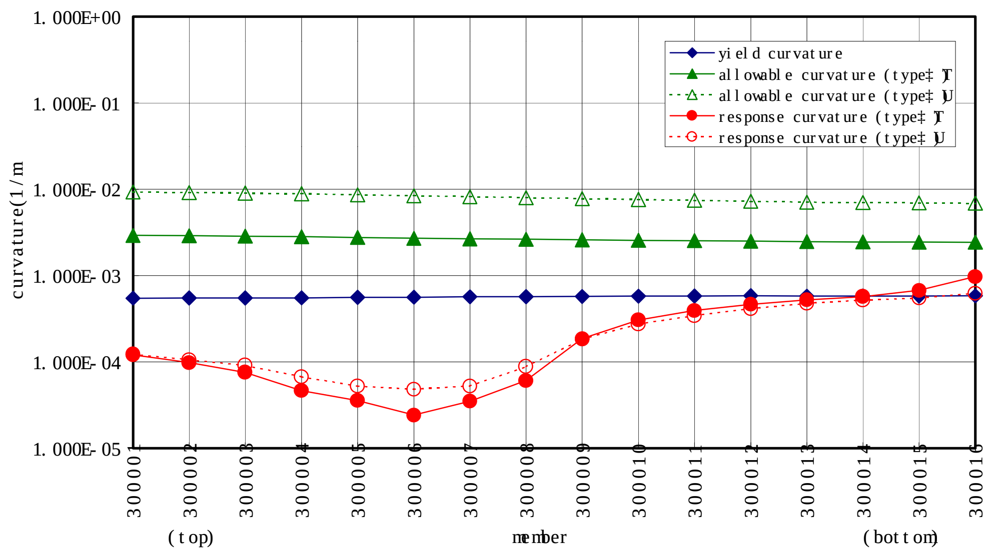

Figure 7: Response curvature and allowable curvature of pier P3

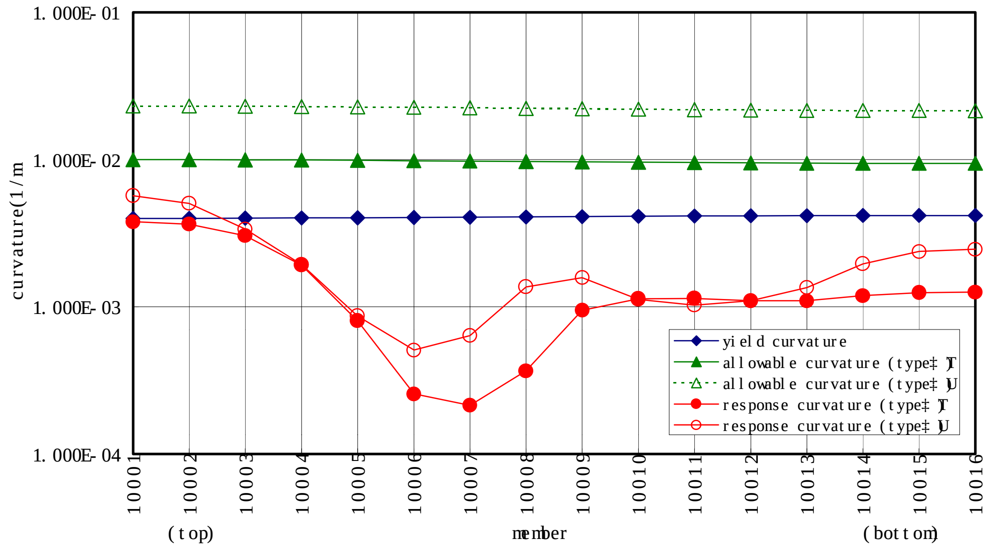

Figure 8: Response curvature and allowable curvature of vertical member V1

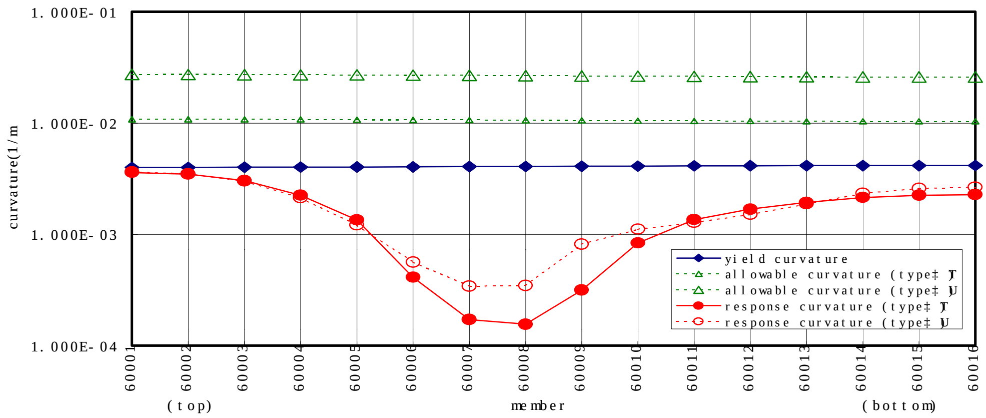

Figure 9: Response curvature and allowable curvature of vertical member V6

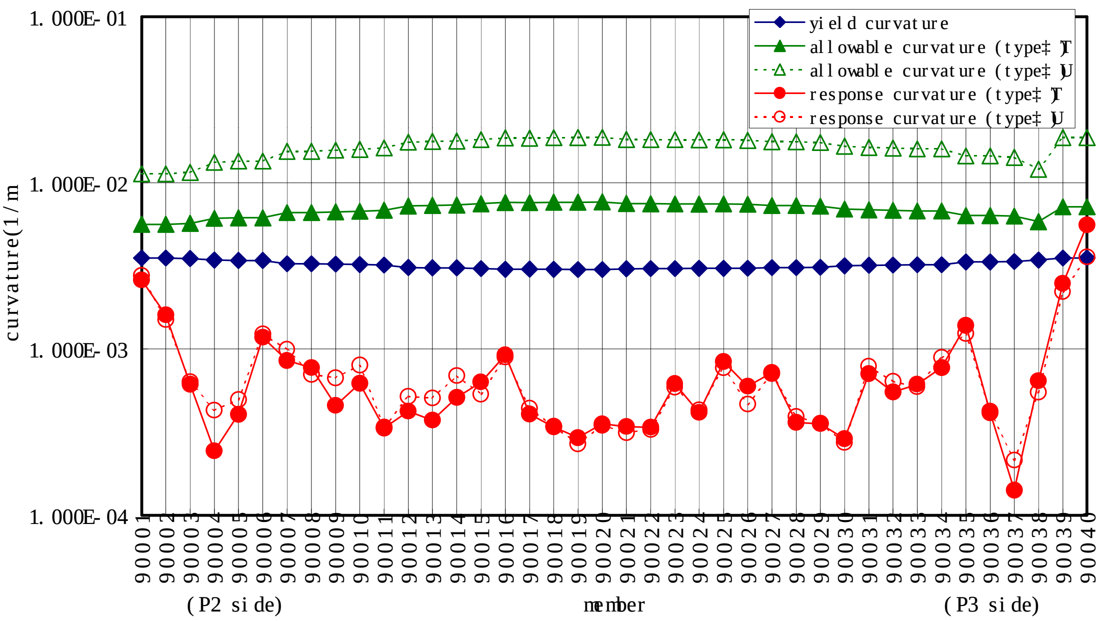

Figure 10: Response curvature and allowable curvature of arch ring

DYNAMIC RESPONSE ANALYSIS CONSIDERING EFFECT OF AXIAL FORCE FLUCTUATION

When effect of axial force fluctuation is considered in dynamic response analysis, nonlinear characteristics (i.e. relationship of flexural moment and curvature) of members change as axial force alters. Generally there are three methods that can be applied to consider axial force fluctuation [2]. These are given below.

1. Flexural moment and curvature are modeled to change according to axial force.
2. Effect of axial force fluctuation is directly considered by using fiber models.
3. Initially, flexural moment and curvature relationship due to axial force acted by dead load are used to determine members that yield, then, different flexural moment and curvature relationship due to maximum and minimum axial force are used to verify effect of axial force fluctuation.

Although methods 1 and 2 directly considers the change in flexural moment and curvature relationship, its actual application to seismic design are few and validity of analytic results are difficult to evaluate. Therefore, in this study, method 3 is used.

Results are shown in Fig. 11 and Fig. 12. Here, response curvatures are found to be within its corresponding allowable values.

CONCLUSIONS

1. According to eigen analysis of the bridge structure considered herein shows that its first vibration mode is dominant.
2. Since the structure shows long period, responses are larger in ground motion Type I than Type II. Responses are within allowable values.
3. In nonlinear dynamic response analysis considering axial force fluctuation, responses due to minimum axial force are larger than that of axial force acted by dead load. Responses are found to be within allowable values.
4. The structure is vulnerable in top and bottom of pier P1, bottom of pier P3, top of vertical member V1 and arch's springing area near pier P3. However, responses are within allowable values.

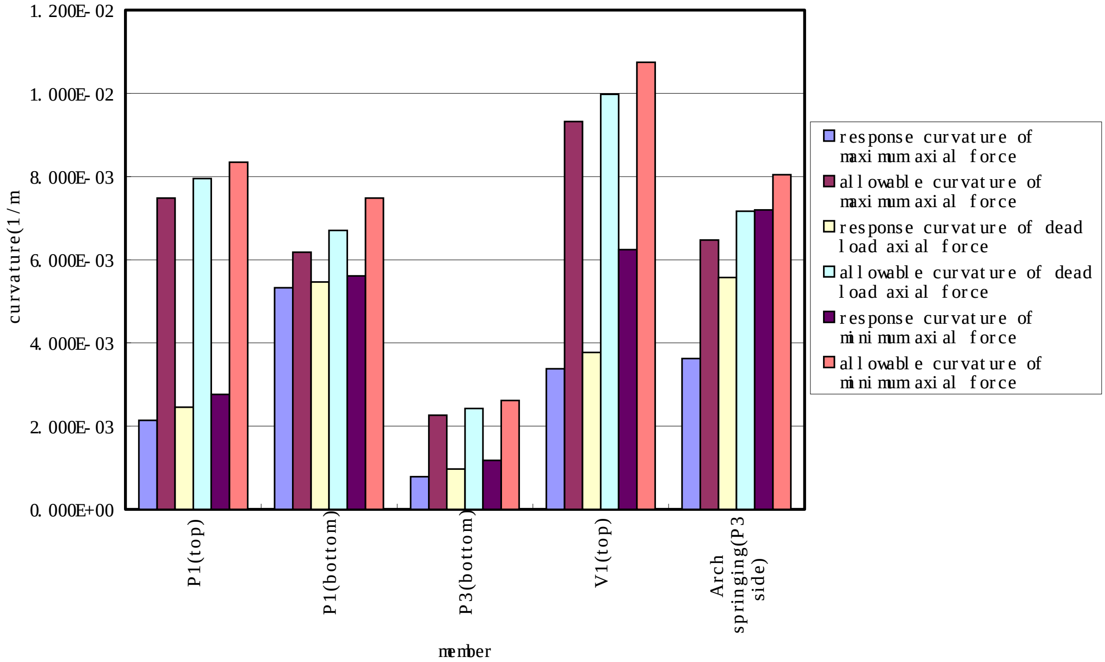

Figure 11: Response curvature and allowable curvature (Type I)

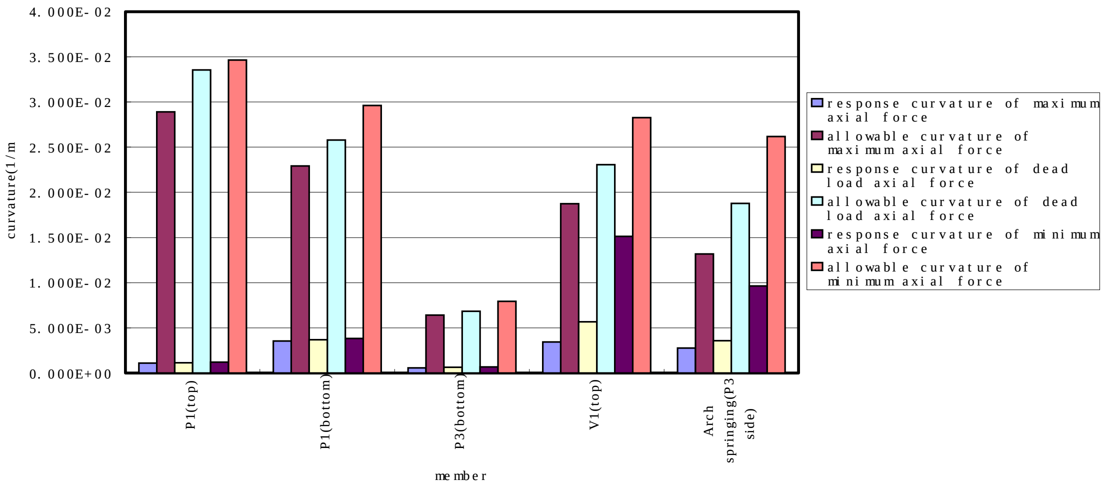

Figure 12: Response curvature and allowable curvature (Type II)

REFERENCES

1. Japan Road Association (1996), *Design Specifications of Highway Bridges, Part V: Seismic Design.*
2. Japan Road Association (1998), *Materials for Seismic Design of Highway Bridges-Seismic Design Examples of PC Rigid Frame Bridge, RC Arch Bridge, PC Cable-stayed Bridge, Underground Continuous Wall Foundation, Board Foundation, etc.*