Study on Seismic Response Analysis of Curved Grillage Girder Viaducts with Base Isolation System under Low Temperature

Hokkaido University	Student member	○ Zhiping GAN
Hokkaido University	Fellow member	Toshiro HAYASHIKAWA
Hokkaido University	Member	Takashi MATSUMOTO
Hokkaido University	Member	Xingwen HE

1. Introduction

Base isolation is a quite sensible structural control strategic design in reducing the response of a structural system induced by strong ground motions[1]. And lead-rubber bearing(LRB) is one of the most widely used base isolation device. In previous studies, various configuration of LRB, such as different properties, transverse fix/isolation setting and mixture combination with another types of bearings were discussed[2]. And in the present study, the effect of low temperature is taken into account as well.

The temperature dependent mechanical behavior of rubber material was first investigated by Gough and Joule in 1805[3]. They concluded that due to the entropy elasticity property of rubber, the elastic response changes with the absolute temperature of the material. In the recent past, several experimental investigations of thermo-mechanical behavior of rubber materials have been conducted by some authors[4),5)]. And Some authors carried out experimental studies of the temperature dependence of rubber bearing based on sinusoidal loading tests[6),7)].

According to these experimental results, the stiffness of LRB increases when temperature is under -10℃. And with the increment of stiffness of LRB, the seismic performance of viaducts varies significantly. Therefore it is necessary to evaluate the temperature effect on LRB in seismic analysis, especially for a designer of cold region such as Hokkaido.

2. Analytical Model of Viaduct

The curved grillage girder viaduct considered in this analysis is a three-span continuous bridge, as shown in **Fig.1**. The overall length of 120m is divided in three equal spans of 40m, The bridge alignment is horizontally curved in a circular arc and the radius of curvature is 100m. And the height of four piers is 20m. The analytical model is shown in **Fig.2**. Superstructure and piers are modeled as beam-column elements. Superstructure is divided into 62 elements and pier is divided into 5 elements.

2.1 Superstructure and substructure

The bridge superstructure consists of a reinforced concrete deck slab that rests on three I-shape steel girders, equally spaced at an interval of 2.1m. The girders are interconnected by end-span diaphragms as intermediate diaphragms at uniform spacing of 10m. And the total weight of superstructure is 8.82MN.

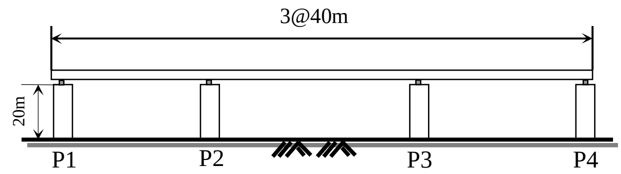


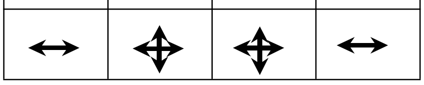
Fig.1 Three-span Continuous Bridge Viaduct

Table 1 Bearing configuration

Case	Product Code	Dimension	Temperature
1	LRB-S-200	side length 200mm	+20℃
2	LRB-S-200LT	side length 200mm	-30℃
3	LRB-S-350	side length 350mm	+20℃
4	LRB-S-350LT	side length 350mm	-30℃
5	LRB-S-500	side length 500mm	+20℃
6	LRB-S-500LT	side length 500mm	-30℃

Table 2 Isolation/Fix Configuration of Bearing

P1	P2	P3	P4



Arrow: Isolation
No Arrow: Fix

In the presented study the viaduct is supported by four steel box section piers, having the same height of 20m. The width of box section is 2.4m, while the thickness is 0.05m. Characterization of the non-linear pier structural is based on the fiber flexural element modeling. The element is divided in 5 longitudinal parts, which, as well are subdivided in 12 transverse divisions. The stress-strain behavior is described by a bilinear model. The yield stress is 235.4MPa, the modulus of elasticity is 200GPa and the strain hardening in plastic area is equal to 0.01.

2.2 Bearing supports

Three bearings systems are considered in the present study. The temperature effect on LRB is also added for comparison. The bearing configuration is summarized in **Table 1** and the isolation configuration of every bearing support is shown in **Table 2**.

3. LRB Under Low Temperature

As shown in **Fig.3**, the rubber-based bearing isolation system consists of layers of rubber and steel, with the rubber being arranged with steel plates one by one for horizontal flexibility and vertical stiffness. LRB consists of a lead-plug insert which provides its characteristic hysteretic energy-dissipation effect. The material lead could provide

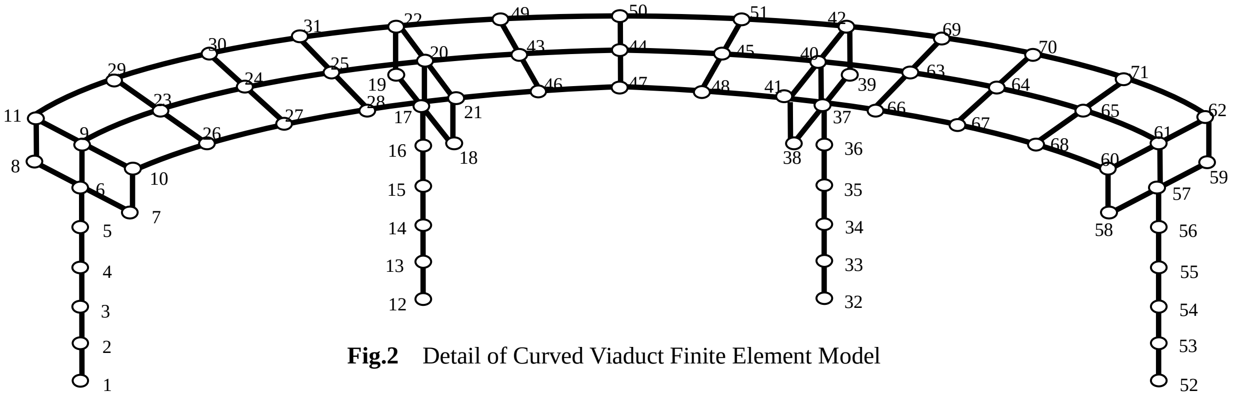


Fig.2 Detail of Curved Viaduct Finite Element Model

large initial stiffness and after yielding it has good anti-fatigue performance.

Under normal conditions, LRB bearings behave like regular bearings. However, in the event of a strong earthquake, with the utilization of this base-isolation system, the superstructure of a bridge is decoupled from its substructure, and the response of the superstructure to the dynamic seismic loading is altered favorably and the seismic dynamic energy transferred to the superstructure is reduced. Thus seismic inertial loads are reduced and the seismic damage the structure acquires is drastically reduced.

3.1 Performance of LRB

The force-displacement relationship of LRB is trilinear hysteretic, as shown in **Fig. 4**. K_1 is initial stiffness and K_2 is yield stiffness. K_3 is introduced to represent the strain hardening at a high shear strain. F_1 is yield force and F_2 is design force.

Usually, design value is not equal to ultimate(failure) value. For the case of LRB, manufacturers[8)] and Japan Road Association[9)] warn constructor not to use LRB over the range of design value, because when force or displacement exceeds design value, hardening happens as shown in **Fig.4**. And when hardening happens, the seismic response of superstructure increases drastically[10)]. However, sometimes the earthquake is so severe that hardening effect could not be avoided. Therefore getting K_3(stiffness after hardening) included in the analytical model is still worthwhile.

3.2 Low temperature effect on LRB

Since LRB is mainly made of rubber, some characteristics of rubber conspicuously influence the performance of LRB. Such as strain hardening effect which has been discussed above, and the stiffness increase under low temperature.

High stiffness basically is not a good property of LRB, it may cause intensive vibration and more response transferred to superstructure. Stiffness increase under low temperature may lead to problems, as well as strain hardening does. Thus, it is necessary to evaluate the the temperature effect on LRB.

Base on the experiment results, for the case of a long-term low temperature accumulation, the equivalent stiffness of LRB increases about 30%. The performance of bearings is summarized in **Table 3**.

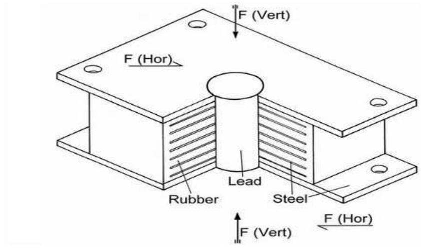


Fig.3 Rubber Bearing with Lead Plug Inside(LRB)

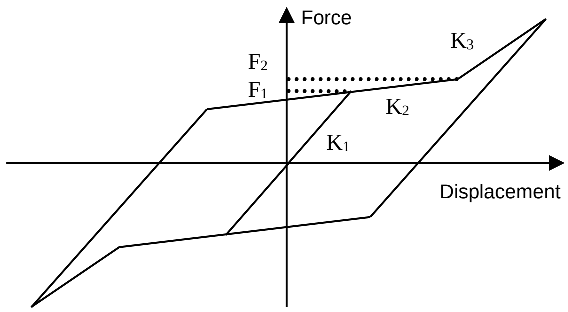


Fig.4 Analytical Model of LRB

4. Numerical Results

Structural responses are examined for all selected types of bearings under the action of earthquake wave. The input motion used for response analysis are acceleration-time history obtained from the Hyogoken-Nanbu earthquake.

Dynamic response analysis of substructure has been focused on a central pier(P3) because central piers support double weight and consequently, the most severe seismic response is found in this structural member.

4.1 Natural vibration analysis

Calculation of natural vibration characteristics of highway viaducts is crucial for prediction of their structural behaviour during strong earthquakes. Natural vibration analysis of the model of viaduct supported on six different cases is carried out, as shown in **Table 4**.

According to the recommendations of Specifications of Highway Bridges, the fundamental natural period of the isolated viaducts with LRB systems are selected to be long enough. The characteristics of the LRB bearings are selected to obtain fundamental periods of 1.780, 1.435s and 1.273s, respectively. These values nearby twice the natural period of the bridge when no isolation bearing is applied(0.856s), as it is recommended by Specifications.

Table 3 Performance of Bearings (K(MN/m)　F(MN))

Case	K_1	K_2	K_3	F_1	F_2
1	1.489	0.212	0.549	0.063	0.125
2	1.936	0.276	0.714	0.082	0.163
3	2.662	0.38	0.984	0.096	0.191
4	3.461	0.494	1.279	0.125	0.248
5	3.850	0.55	1.425	0.138	0.275
6	5.005	0.715	1.853	0.179	0.358

Table 4 Fundamental Natural Frequencies and Periods

Case	ω [rad/sec]	T[sec]	ratio to T of fix
1	3.530	1.780	2.08
2	3.905	1.609	1.80
3	4.379	1.435	1.68
4	4.774	1.316	1.54
5	4.936	1.273	1.49
6	5.320	1.181	1.38
All-Fix	7.340	0.856	1

And since stiffness of LRB increases under low temperature, case 2, case 4 and case 6(-30℃) have a shorter natural period than case 1, case 3 and case 5(+20℃). This is, obviously, an unfavorable phenomenon.

4.2　Shear force-displacement response at bearing

Shear Force-Displacement relationship at bearing is an important response parameter for seismic analysis. To limit peak shear force, the bending moment transferred to the base of piers is under control; to limit the maximum bearing displacement, deck displacement is limited and collision between deck and abutment is avoided.

Shear force-displacement response at bearing of different cases are shown in **Fig.5**. It is clearly appreciated that LRB bearings effectively reduce inertial forces acting on bridge piers. Hardening effect is observed in case 1 and case 2. And under low temperature, with the increment of stiffness, the deformation of bearing decreases.

4.3　Bending moment-curvature response

In most cases, structural damage due to earthquakes can be attributed to the plastic hinges formed at piers of the bridge. The bending moment at the base of piers is considered to be a good measure to decide the damage level.

Bending Moment-Curvature Response at the base of piers are shown in **Fig.6**. The yield moment of the pier is 84.8MN, and therefore inelastic deformation occurs in all the cases. But LRB bearings can substantially reduce the seismic forces on piers. Under low temperature, with the increment of stiffness, the curvature of the base of piers remarkably increases.

4.4　Energy-time history

During earthquake, input energy flows from the ground to structure and should be dissipated by structure vibration(kinetic energy), damping mechanism(damping energy) and plastic deformation(strain energy).

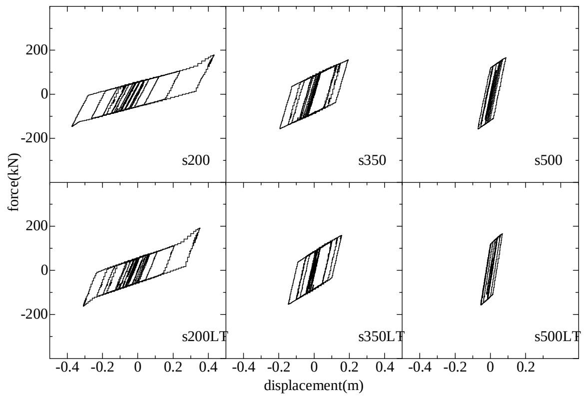


Fig.5 Shear Force-Displacement Response at Bearing

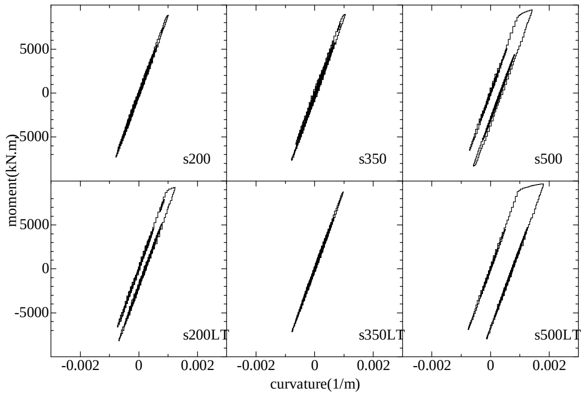


Fig.6 Bending Moment-Curvature Response

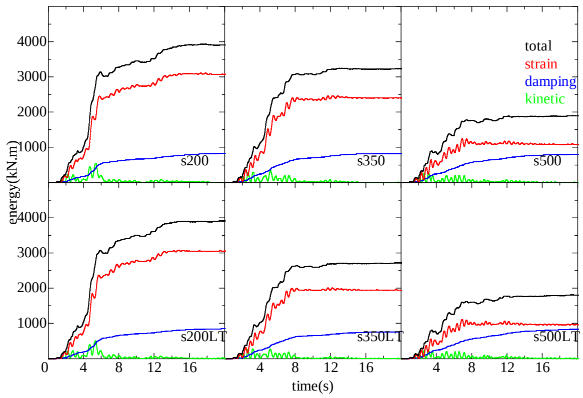


Fig.7 Energy-Time History

Energy is used as an alternative response factor to evaluate response quantities like force or displacement to examine the seismic damage effect on bridge structures. The performance of the bearing systems is analyzed by comparing the energy-time histories, as shown in **Fig.7**.

The obtained results show that the amount of seismic energy inputted to the viaduct depends highly on the structural characteristics such as natural period and damping properties. A LRB system with lower stiffness has more deformation capability, therefore could dissipate more strain energy. And low temperature makes LRB harder, consequently energy dissipation decreases. This is another unfavorable phenomenon under low temperature.

4.5 Displacement-time history at deck

Maximum deck displacement is a relevant parameter for bridge design, it defines the gap between deck and abutment because exciting earthquakes always cause larger displacement in abutment. Large displacement may cause large force to superstructure due to collision between deck and abutment.

For isolated bridge structures, deformation of isolation bearings usually results in large peak deck displacements. However, it is necessary to provide sufficient clearance for displacements to occur, avoiding the possibility of impacts with the abutments. Displacement-time histories of different cases are shown in **Fig.8**. Residual deck displacement, caused by the residual curvature generated by inelastic deformation at the pier base, is observed. And temperature effect is not so significant in this section.

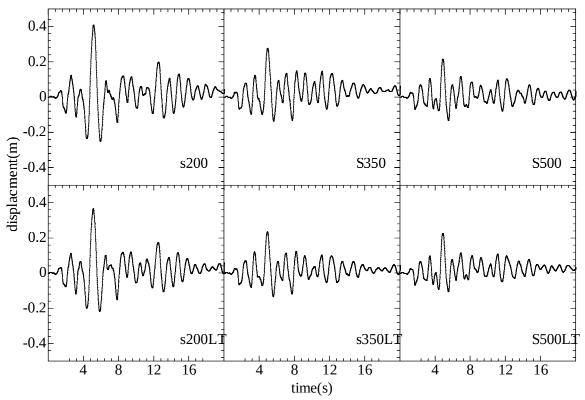


Fig.8 Displacement-Time History at Deck

5. Conclusions

In the present study, nonlinear dynamic analysis of a finite element model of highway viaduct with various support configuration is carried out. Seismic responses are studied and compared to investigate the influence of bearing conditions on the overall behaviour of the bridge. And the conclusions are:

(1) According to the mechanism of the LRB device, LRB device with smaller dimension usually has lower stiffness. And LRB with low stiffness has better performance. Longer natural period and more bearing deformation make it dissipate more energy generated by earthquake ground motion. This is just the function of isolation system. But the problem is, the deformation capacity of a LRB device with smaller dimension is less as well, i.e. the product fails easily and encounters hardening effect easily. Therefore a proper LRB device should be carefully chosen, satisfying not only performance but also safety.

(2) As suggested by speciations, hardening effect of LRB should be avoided as much as possible. According to the comparison of case 1,2 and case 3,4, hardening effect significantly increase the peak shear force, thus leading to worse performance of LRB devices. And according to the comparison of case 1 and case 2, low temperature will amplify the hardening effect. The combination of these two negative effects absolutely subverts the regular rule of performance of LRB, additional attention should be paid seriously.

(3) Low temperature makes stiffness of LRB increase. On the other hand, it does not enhance the deformation capacity of LRB. Therefore, low temperature effect should be considered as a pure unfavorable factor. However, according to the comparison of case 3 and case 4, a properly chosen LRB is affected slightly under low temperature. And this numerical analysis result agrees well with the previous experimental investigation.

References

1) Hayashikawa T. Bridge Engineering. Asakura Publishing Co., Ltd, 2000.
2) Ruiz Julian FD and Hayashikawa T. Nonlinear seismic response of highway viaducts with different bearing supports. Proceedings of the 7th Symposium on Ductility Design Method for Bridges, pp.31-38, 2004.
3) Treloar LRG. The Physics of Rubber Elasticity, 3/e. Oxford Univ. Press, 1975.
4) Lion A. On the large deformation behavior of reinforced rubber at different temperatures. J. Mech. Phys.Solids, 45, pp.1805-1834, 1997.
5) Hwang JS, Wu JD, Pan T,C, Yang GA. Mathematical hysteretic model for elastomeric isolation bearings. Earthquake Engrng. Struct.Dyn.31, pp.771-789, 2002.
6) Khan AS and Lopez-Pamies O. Time and temperature dependent response and relaxation of a soft polymer, Intl. J. Plast, 8, pp.1359-1372, 2002.
7) Oshima T, Mikami S, Yamazaki T, Ikenaga M, Matsui Y and Kubo K. Experimental of functional confirmation on lead rubber bearing (LRB) under low temperature. J. Struct. Engrg. 44A, pp.753-760, 1998.
8) Product Prospectus of Mageba sa, 2012.
9) Japan Road Association. Specification for Highway Bridges, Part V: Seismic Design. 2002.
10) Adachi Y and Unjoh S. Seismic response characteristics of seismically isolated bridge considering hardening effect of seismic isolator where non-linear response occur at both seismic isolator and bridge column. Journal of Structural Engineering Vol.47A, pp.905-916, 2001.