Nonlinear Seismic Dynamic Response of Continuous Curved Highway Viaducts with Different Bearing Supports

Rinna Tanaka, Carlos Mendez Galindo, Toshiro Hayashikawa

Abstract**—**The results show that the bridge equipped with seismic isolation bearing system shows a high amount of energy dissipation. The purpose of the present study is to analyze the overall performance of continuous curved highway viaducts with different bearing supports, with an emphasis on the effectiveness of seismic isolation based on lead rubber bearing and hedge reaction force bearing system consisted of friction sliding bearing and rubber bearing. The bridge seismic performance has been evaluated on six different cases with six bearing models. The effects of the different arrangement of bearing on the deck superstructure displacements, the seismic damage at the bottom of the piers, movement track at the pier's top and the total and strain energies absorbed by the structure are evaluated. In conclusion, the results provide sufficient evidence of the effectiveness on the use of seismic isolation on steel curved highway bridges.

Keywords**—**Curved highway viaducts, non-linear dynamic response, seismic damage.

I. INTRODUCTION

CURVED alignments offer the benefits of aesthetically pleasing, traffic sight distance increase, as well as economically competitive construction costs with regard to straight bridges. On the contrary, bridges with curved configurations may sustain severe damage owing to rotation of the superstructure or displacement toward the outside of the curve line due to complex vibrations occurring during an earthquake [1]. Most existing viaducts are simply single span, which is inexpensive to construct. However the expansion joint makes that traveling performance deteriorated and the noise, vibration and leaked water proceeded. So it takes more costs and time for maintenance. And the repair work often causes tie up. Therefore recently constructed viaducts are adopted continuous span.

To make the span continuous, some devices are needed in the bearings as to prevent concentration of the horizontal seismic force in a single pier and disperse seismic force to each pier. Also the stretching behavior of the girder length caused by temperature alteration should be reduced.

In addition, another commonly adopted earthquake protection strategy consists of replacing the vulnerable steel bearings with isolation devices. Among the great variety of seismic isolation systems, lead-rubber bearing (LRB) has found wide application in bridge structures. This is due to their simplicity and the combined isolation-energy dissipation function in a single compact unit. The LRB bearings are steel reinforced elastomeric bearings in which a lead core is inserted to provide hysteretic damping as well as rigidity against minor earthquakes, wind and service loads [2]. However LRB support system restricts ground and structural assumption. LRB support system is rather expensive.

As a new type of bearing system, hedge reaction force bearing system has been come up. Hedge reaction force bearing system consists of friction sliding bearing and rubber bearing. Hedge reaction force bearing system work similarly to LRB and its cost is lower than LRB.

LRB support system and hedge reaction force bearing system make the viaduct long period and heavy damped. So it is concerned that the amount of horizontal displacement becomes bigger. The displacement may overreach the expansion gap or the maximum permitted value of bearing.

Even though the application of the mentioned earthquake protection techniques, the considerable complexity associated with the analysis of curved viaducts requires a realistic prediction of the structural response, especially under the extreme ground motions generated by earthquakes.

Therefore, the purpose of the present study is to analyze the overall performance of highway viaducts with different sequence of the five kinds of bearings. The study combines the use of non-linear dynamic analysis with a three-dimensional bridge model to accurately evaluate the seismic demands on kind of baearing in the event of severe earthquakes.

II. ANALYTICAL MODEL OF VIADUCT

The great complexness related to the seismic analysis of highway viaducts enhances a realistic prediction of the bridge structural responses. This fact provides a valuable the structure on the stresses and forces. Therefore, the seismic analysis of the viaduct employs non-linear computer model that simulates the highly non-linear response. Non-linearity is also considered for

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characterization of the non-linear structural elements of piers and bearings. The highway viaduct considered in the analysis is composed by a three-span continuous seismically isolated section. The overall viaduct length of 120 m is divided in equal spans of 40m, as represented in Fig. 1. The bridge alignment is horizontally curved in a circular arc. The radius of curvature is 100 m measured from the origin of the circular arc to the centerline of the bridge deck. Tangential configuration for both piers and bearing supports is adopted, respect to the global coordinate system for the bridge, shown in the figure, in which the X- and Y-axes lie in the horizontal plane while the Z-axis is vertical.

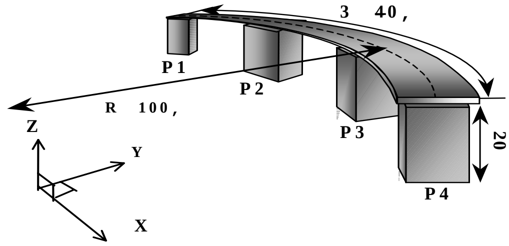
A. *Deck superstructure and piers*

The bridge superstructure consists of a concrete deck slab that rests on three I-shape steel girders, equally spaced at an interval of 2.1 m. The girders are interconnected by end-span diaphragms as well as intermediate diaphragms at uniform spacing of 5.0 m. Full composite action between the slab and the girders is assumed for the superstructure model, which is treated as a three-dimensional grillage beam system shown in Fig. 1.

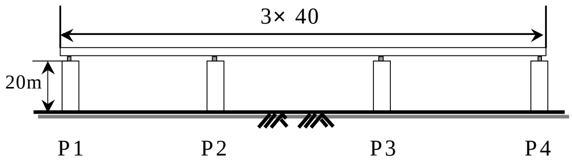
The deck weight is supported on four hollow box section steel piers. The piers are 20m height designed according to the seismic code in Japan [1]. Characterization of structural pier elements is based on the fiber element modeling where the inelasticity of the flexure element is accounted by the division of the cross-section into a discrete number of longitudinal and transversal fiber regions with constitutive model based on uniaxial stress-strain relationship for each zone. The element stress resultants are determined by integration of the fiber zone stresses over the cross section of the element. At the pier locations the bridge deck is modeled in the transverse direction as a rigid bar of length equal to the deck width. This transverse rigid bar is used to model the interactions between deck and pier motions [3].

B. *Bearing supports*

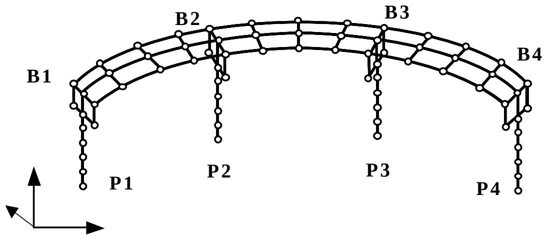
The continuous span is supported on four pier units (P1, P2, P3 and P4). The same kinds of bearing supports are installed across the full width of the pier. In this research, three kinds of bearing and its combinations are compared. The analytical models of bearing supports are shown in Fig. 3. The steel fixed bearing does not allow for movement in any direction. Generally, it imparts the earthquake energy or vibration to the pier. The steel fixed bearing is modeled by using the linear displacement-load relationship as shown in Fig. 3 (a). The steel movable bearing allow for movement in the longitudinal (tangent to the curved superstructure) direction while restrained in the transverse radial direction. Coulomb friction force is taken into account in numerical analysis for roller bearings, which are modeled by using the bilinear rectangle displacement-load relationship, shown in Fig. 3 (b) LRB bearings is such as to allow for longitudinal and transverse movements. LRB supports are represented by the bilinear force-displacement hysteresis loop presented in Fig. 3 (c).



(a) 3D view of viaduct



(b) Elevation view of viaduct



(c) Detail of curved viaduct finite element model

Fig. 1 Model of curved highway viaduct

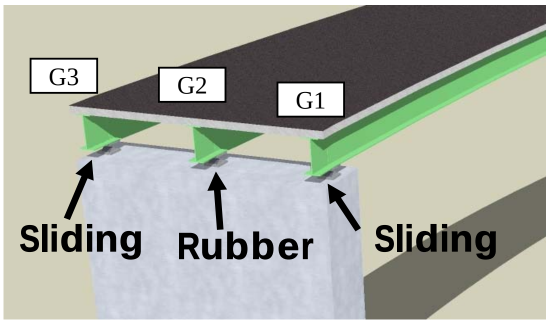


Fig. 2 Hedge reaction force bearing system(R)

The principal parameters that characterize the analytical model are the pre-yield stiffness K_1, corresponding to combined stiffness of the rubber bearing and the lead core, the stiffness of the rubber K_2 and the yield force of the lead core F_1. The devices are designed for optimum yield force level to superstructure weight ratio (F_1/W = 0.1) and pre-yield to post-yield stiffness ratio (K_1/ K_2 = 10.0), which provide maximum seismic energy dissipation capacity as well as limited maximum deck displacements [4]. It is also noted that properties of LRB supports have been selected depending on the differences in dead load supported from the superstructure.

TABLE I
BEARING COMBINATION

F-M-M-M	Fix	Movable	Movable	Movable
M-F-F-M	Movable	Fix	Fix	Movable
LRB's	LRB	LRB	LRB	LRB
F-S-S-S	Fix	Sliding - Rubber	Sliding - Rubber	Sliding - Rubber
S-R-R-S	Sliding - Rubber	Rubber	Rubber	Sliding - Rubber
R-S-S-S	Rubber	Sliding - Rubber	Sliding - Rubber	Sliding - Rubber

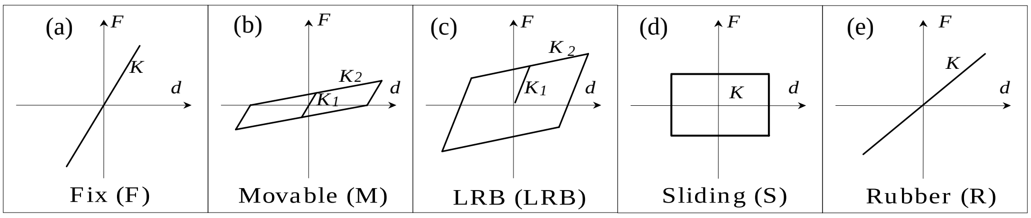


Fig. 3 Analytical models of bearing supports

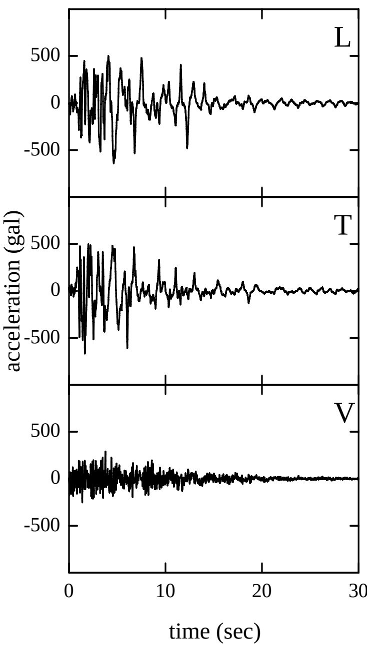


Fig. 4 JR Takatori St. Record, 1995 Kobe Earthquake.

The objective is to attract the appropriate proportion of non-seismic and seismic loads according to the resistance capacity of each substructure ensuring a near equal distribution of ductility demands over all piers. Furthermore, displacements of LRB supports have been partially limited for all the viaducts, through the installation of lateral side stoppers.

Orientation of the hedge reaction force bearing system shown in Fig. 2 consists of friction sliding bearing and rubber bearing (S). The friction sliding bearing holds vertical load. The rubber bearing works horizontal force.

The viaduct model has three girders. The friction sliding bearings are placed outside girder and inside girder of the curvature. The rubber bearing is placed middle girder.

The sliding bearing dissipates seismic horizontal energy with its friction force. The sliding bearing is modeled bilinear force-displacement hysteric loop using high stiffness property to pre-yield stiffness and approximate zero to post-yield stiffness as shown in Fig. 3 (d).

The rubber bearing is restrained in the transverse radial direction and vertical direction. The rubber bearing is modeled by using the linear displacement-load relationship. It handles vertical load. The yield stiffness (K) is 250MN/m. The Rubber bearing is modeled by using the linear displacement-load relationship as shown in Fig. 3(e). The combinations of the bearings in the research are summarized in the Table I.

III. ANALYTICAL METHOD

The analysis on the highway viaduct model is conducted using an analytical method based on the elasto-plastic finite displacement dynamic response analysis. The tangent stiffness matrix, considering both geometric and material nonlinearities is adopted in this study, being the cross sectional properties of the nonlinear elements prescribed by using fiber elements. The stress-strain relationship of the beam-column element is modeled as a bilinear type. The yield stress is 235.4 MPa, the elastic modulus is 200 GPa and the strain hardening in plastic area is 0.01. The implicit time integration Newmark scheme is formulated and used to directly calculate the responses, while

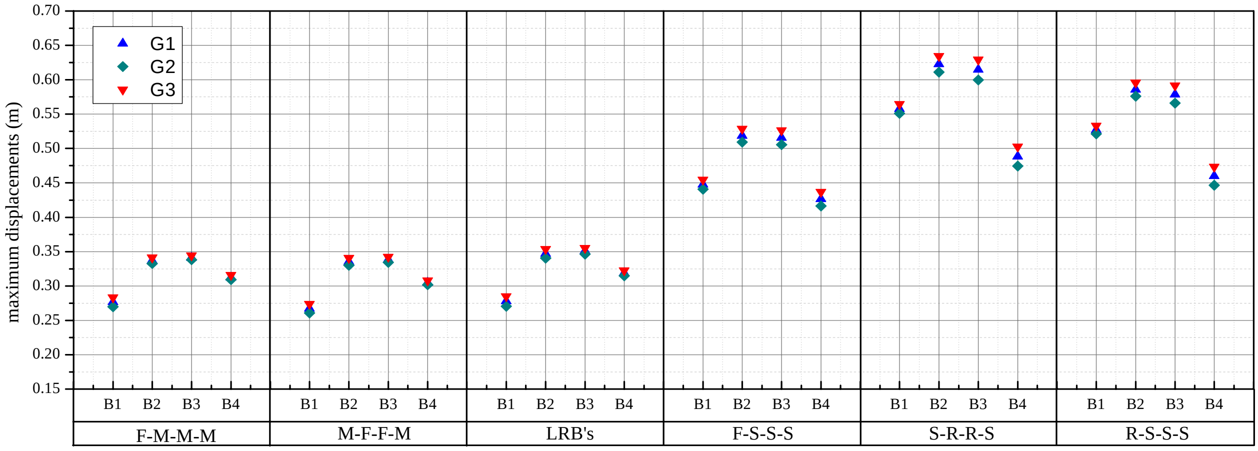


Fig. 5 Maximum deck displacements on superstructure

the Newton-Raphson iteration method is used to achieve the acceptable accuracy in the response calculations. The damping of the structure is supposed a Rayleigh's type, assuming a damping coefficient of the first two natural modes of 2%.

To assess the seismic performance of the viaduct, the nonlinear bridge model is subjected to the longitudinal (L), transverse (T), and vertical (V) components of a strong ground motion records from the Takatori Station during the 1995 Kobe Earthquake as shown in Fig. 4. The longitudinal earthquake component shakes the highway viaduct parallel to the X-axis of the global coordinate system, while the transverse and vertical components are acting in the Y- and Z-axes, respectively.

The large magnitude records from the 1995 Kobe Earthquake used in this study, classified as near-fault motions, are characterized by the presence of high peak accelerations and strong velocity pulses with a long period component as well as large ground displacements [5]. These exceptionally strong earthquakes have been selected due to the destructive potential of long duration pulses on flexible structures.

IV. Numerical Results

The overall three-dimensional seismic responses of the viaducts are investigated in detail through non-linear dynamic response analysis. In the result, a lot of distinctions caused by the different kind of bearing and the combinations of the bearings are observed.

A. Deck superstructure displacement

Firstly, the effect of the kind of bearings on deck displacement is analyzed. The tangential direction to the curved girder is shown on the displacement of the superstructure. The restrained sequence girder viaducts are analyzed in terms of the maximum displacement on the steel roller bearing, the steel fixed bearing, the LRB support and the hedge reaction force bearing with the rubber bearing and the sliding bearing. The results, shown in Fig. 5, indicate that in the each middle two piers, the maximum displacement of the deck is bigger than in the each outside two piers. And the maximum displacements observed in the middle two piers are much the same values.

Both of the case F.M.M.M, the case M.F.F.M and the case LRB show smallest displacement on the B1, while the case F.S.S.S, the case S.R.R.S and the case R.S.S.S shows smallest displacement on the B4.

The differences between the B2-B3 (observed larger displacement) and the B1 (observed smallest displacement) are about 0.08 m in the cases of the steel bearings combination and LRB support. While, in the cases of the hedge reaction force bearing combination, the smallest displacement is observed at B4, the displacement differences are about 0.12m. Compared with the 3 girders in the same pier, the girder of G3 (most outside of the girders) is observed the largest displacement. And the value of differences on the same piers observed each girder reaches about 0.25m. The combination of the sliding bearing and Rubber bearing causes obviously different result with the combination of the steel bearings and LRB. In the result of three cases with hedge reaction force bearing, the almost twice displacement of the steel bearings combinations and LRB is observed. The case S-R-R-S shows over 0.60m of the maximum displacement and about 0.5m at the edge of the girder (B4). The case F-S-S-S using steel fixed bearing shows smaller displacement than the other hedge reaction force bearing cases.

B. Curvature at pier's bottom

The steel fixed bearing sometimes cause serious damage in the pier suffered by earthquake. The results obtained from the analysis in the combinations of bearings are shown in Fig. 6. Firstly, on the direction x, obviously the case with steel bearing is observed large moment. The curvature observed in the case LRB and the three case of the hedge reaction force bearing systems is very small. It means that all the piers, which settle LRB supports and the hedge reaction force bearing system are not influenced in the earthquake, and they do not suffer damage. On the other hand, the steel fixed bearing causes especially large curvature. The pier settles fixed bearing has large moment and it

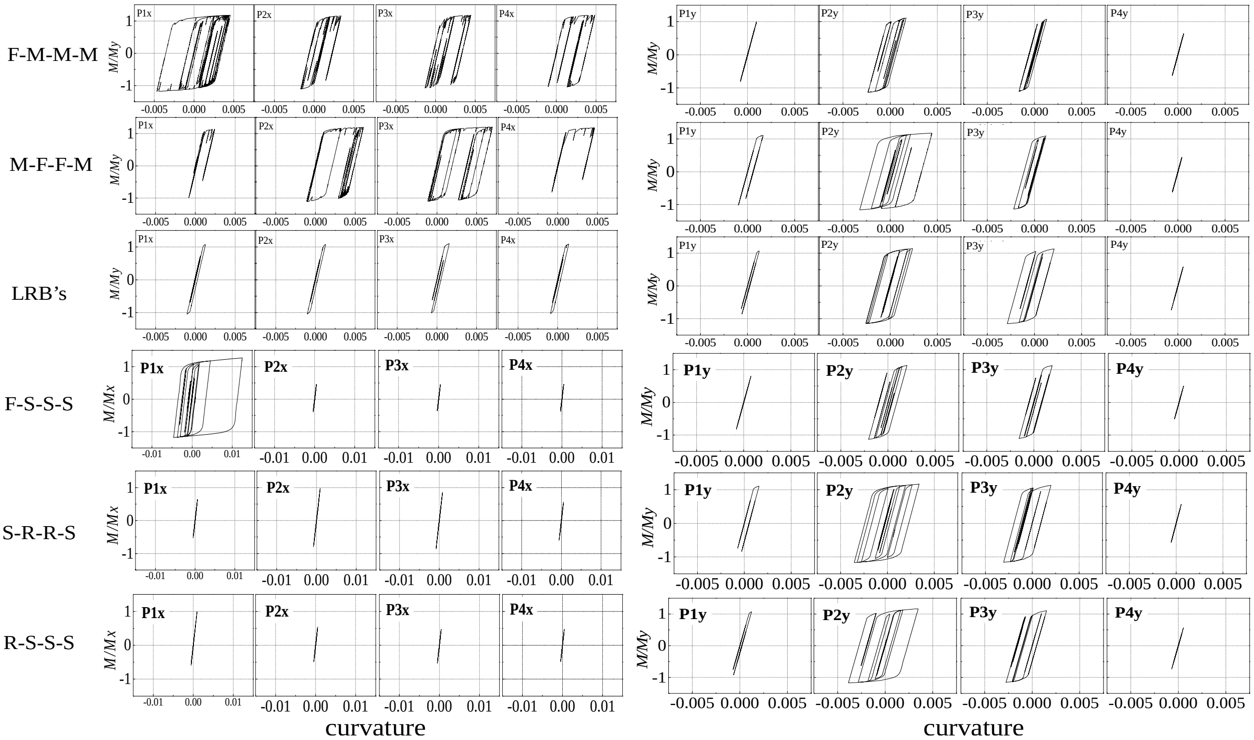


Fig. 6 Curvature moments at pier's bottom

takes a lot of damage from the earthquake. At the same time, the piers settling movable bearing is observed reasonable amount of curvature. At the P1 of the case M.F.F.M, the curvature is small. However in other cases, the curvature is middle large amount. Second, on the direction y, the P1 and the P4 are observed very small curvature and the P2 and P3 are observed some curvature in all cases. That is why all bearings are fixed on the direction. Secondly, on the direction y, especially at the P2 and P3 are observed large moment. The smallest curvature is observed on P4. It indicates that the P2 and the P3 are perishable on all cases.

C. *Energy received from earthquake*

The Fig. 7 shows strain energy and the Fig. 8 shows total energy received from the earthquake. The result indicates the effect of the kind of bearing and the combinations of the bearings. Both strain energy graph and total energy graph of variants are almost interlocking. The difference between the strain energy and total energy at the end of the graph is the biggest of the case S.R.R.S. While the case LRB and the case F.S.S.S is observed small differences. On the strain energy, the case F.S.S.S shows large strain energy, but this bearing acquaints seismic ground motion energy to the pier and it does not mean the bearing reduce seismic fictitious force. The case LRB is the second biggest strain energy, it means mostly reduce seismic fictitious force. The case S.R.R.S and RSSS show near result to the case LRB. The case S.R.R.S is effective for the seismic resistant

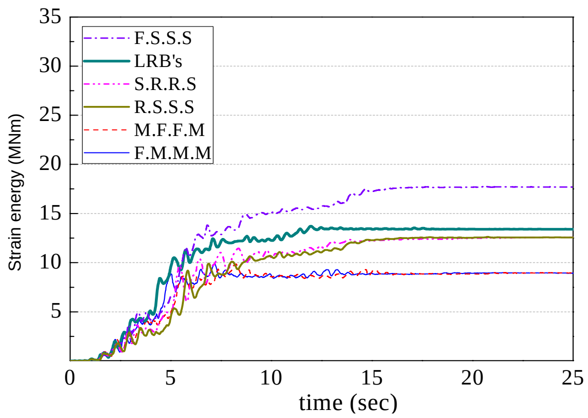


Fig. 7 Strain energy

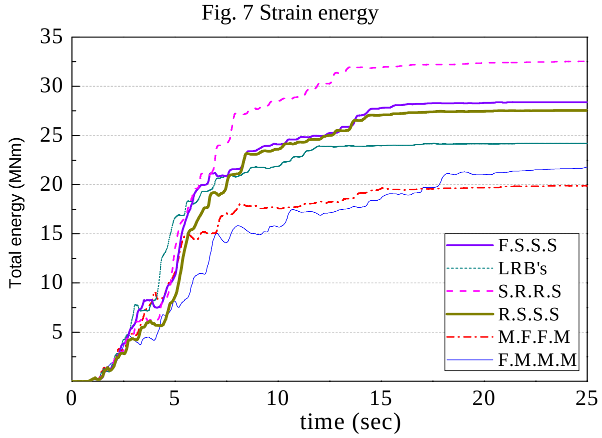


Fig. 8 Total energy

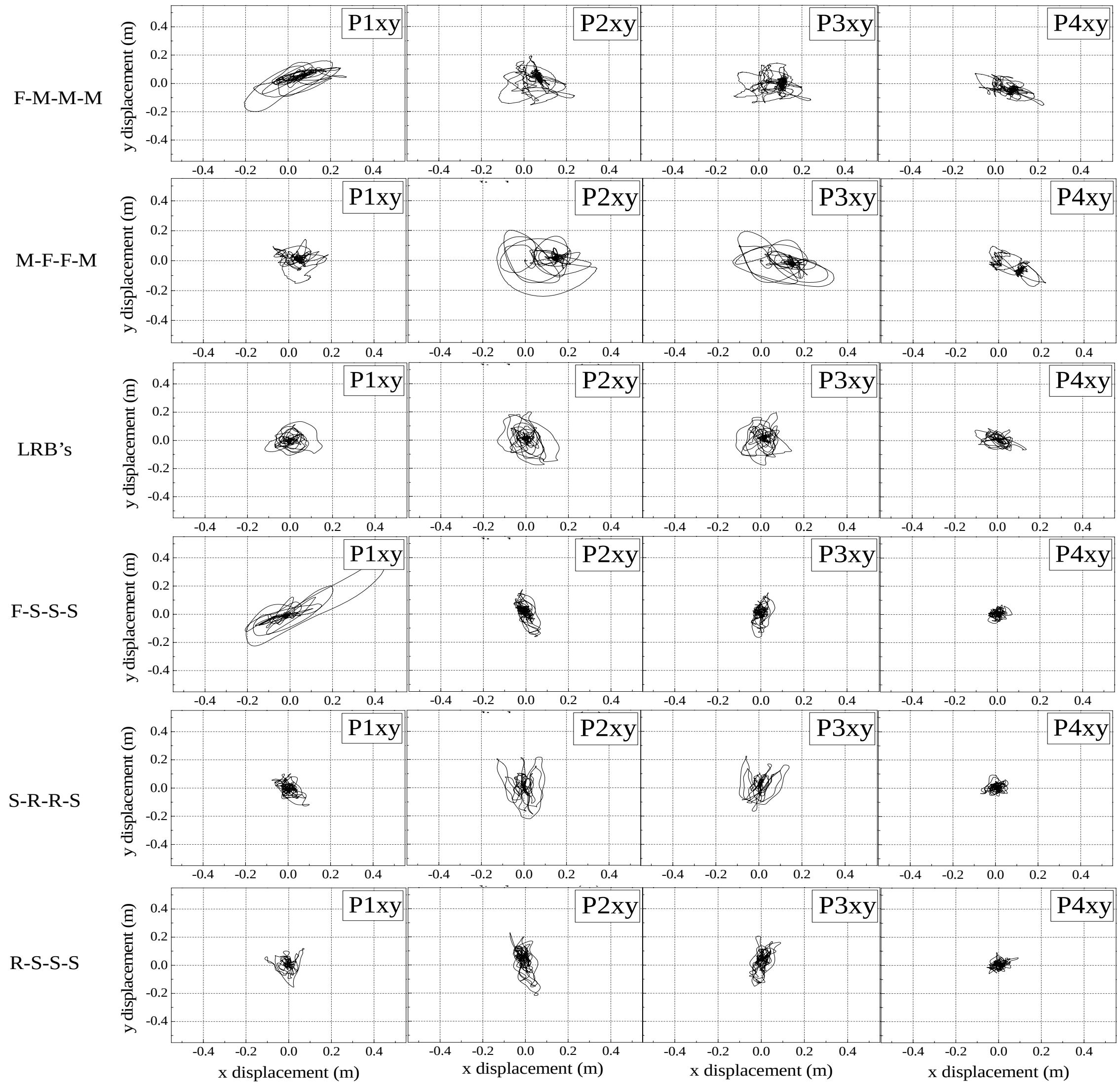


Fig. 9 Pier top displacement trajectories

because the case S.R.R.S shows the biggest both total energy and strain energy.

D. Movement track at pier's top

The Fig. 9 shows the track at the pier's top. Large size of the displacement at pier's top are observed on the steel bearings, especially on the steel fixed bearing. On the case FSSS at P1 with fixed bearing is observed over the 0.4m of displacement on both x and y direction. That is because steel fixed bearing transmit seismic force to only P1. While Small size of movement track are observed on the rubber and sliding bearing. The track on the RSSS is the smallest in all the piers, so this case mostly convey less seismic force to the piers. On the P2 and P3 settled sliding bearing system show ellipsoidal shape. The result indicate that the sliding bearing system reduce seismic force especially x direction. On the other hand, the result on the pier settled rubber bearing shows round shape. This result indicates the rubber bearing system effect isotropicaly. The result also indicate that the kind of the bearing support system, the direction of settling bearings and the curved shape of the viaduct effect on the part of seismic damage.

V. CONCLUSIONS

The effects of the six different kinds of bearing and the combinations of the bearings on nonlinear seismic response of curved highway viaducts have been analyzed.

The continuous curved highway viaduct model is verified on the deck superstructure movement, the moment of the pier's bottom, the strain and total energies and movement track at each pier's top.

The effectiveness of bearings for the superstructure and the piers in the amount of earthquake energy on curved steel viaducts is evaluated. For this purpose, important bridge elements as well as the global structural response have been examined in detail under the action of near-fault earthquake ground motions.

1) The result shows the maximum displacement of the deck superstructure is very large in the case hedge reaction force bearing system. The twice weight loaded on the inside two piers makes the displacements of the two bigger than outside of two piers. In almost all cases were calculated as larger value on G3 than G2 and G1. That is because G3 is the most outside of girder and that is slightly longer, so the girder G3 should move more.

2) The results of the moment of the pier's bottom show the fixed bearing get much curvature. That is why the capacity of the fixed bearing does not accord the superstructure movement. That makes much force of the earthquake reach to the pier. The bearing of movable is allows unidirectional movement for the superstructure. It causes less force reached to the piers. The LRB support, rubber bearing and sliding bearing allow movement. The force of the earthquake does not transmit so much to the pier. It means the force of the earthquake is taken in the bearing sanction and in the motion energy of the superstructure.

The results of the moment of the pier's bottom on the direction Y indicate that the curvilinear shape effects on the middle two piers (P2, P3) observed moment, bigger than that of outsides (P1, P4). The curved figure restrains movement of the viaducts, and it helps the force be carried to the piers. The calculation results obviously show these tendencies in the kinds of bearing.

3) Compared on energy of each case, much high energy is observed in the case of seismic isolate bearing system (LRB, Sliding bearing) than steel bearing cases. That is because the bearing takes in much energy depend on the forces produced by the earthquake. That is because the LRB and sliding bearing displacement behaves bi-linearly on the forces. So they take in some energy from the earthquake. While Steel bearings displacements act linearly on the forces. That's why they do not get energy from the earthquake. Therefore the case of LRB and hedge reaction force bearing system shows higher energy than others. The calculation results obviously show these tendencies in the kinds of bearing. The calculation results obviously show the relation between the moment and energy.

4) The result on the movement track at the pier's top explains the seismic isolation effect on the LRB and sliding bearing and rubber bearing combination system. It shows obviously small influence for the seismic ground motion. While, the result also shows steel bearing especially fixed bearing extend its pier the earthquake force.

REFERENCES

[1] Japan Road Association (JRA), Specifications for Highway Bridges – Part V Seismic Design, Maruzen, Tokyo, 2002.

[2] Mendez Galindo C., Hayashikawa T, Deck unseating damage of curved highway viaducts under Level II Earthquake Ground Motion, *Proceeding of Hokkaido Chapter of the Japan society of civil engineers*, No.64, A-29, 2008.

[3] Jintarou Nakai, Hayashikawa T, A study on nonlinear dynamic response of a curved viaduct system with middle friction sliding bearing under level II earthquake, *Proceeding of Hokkaido Chapter of the Japan society of civil engineers*, No.64, A-21, 2008.

[4] Mendez Galindo C., Hayashikawa T., Ruiz Julian D., Pounding and Deck Unseating Damage of Curved Highway Viaducts with Piers of Unequal Heights, *Journal of Constructional Steel*, JSSC, Vol. 15, pp. 285-292, 2007.

[5] Ali H.M., Abdel-Ghaffar A.M. Modeling the nonlinear seismic behavior of cable-stayed bridges with passive control bearings. *Computer & Structures*, Vol. 54, No.3, pp. 461-92, 1995.