Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015
Division V, Paper ID 700

SEISMIC RESPONSE ANALYSIS OF ISOLATED BUILDING CONSIDERING POSITION AND NONLINEARITY OF RUBBER BEARINGS

Keisuke Minagawa[1], Satoshi Fujita[2], and Yuki Hase[3]

[1] Associate Professor, Department of Mechanical Engineering, Saitama Institute of Technology, JAPAN
[2] Professor, Department of Mechanical Engineering, Tokyo Denki University, JAPAN
[3] Graduate Student, Department of Mechanical Engineering, Graduate School of Tokyo Denki University, JAPAN

ABSTRACT

Seismic isolation is one of effective technologies that can mitigate seismic force and improve seismic reliability, and rubber bearings are usually used as isolation device. Generally, the rubber bearings deform linearly and have linear stiffness against seismic load in both horizontal and vertical direction. However, hardening in the horizontal direction and softening in the vertical direction occur in case of large deformation. Moreover the horizontal hardening properties depend on vertical load. In addition, very large response by large earthquakes should be considered in seismic PRA. Therefore it is important to consider these nonlinear characteristics and the coupling effect in order to improve reliability of seismic isolated buildings.

Authors have already reported results of seismic response analysis of an isolated reactor building considering nonlinearity and its coupling effect of rubber bearings in the previous SMiRT 21 and 22. In this paper, the seismic response analysis model that authors used in previous papers is improved. The new analysis model can consider position of rubber bearings and rocking motion of the building.

A seismic response analysis model which consists of a mass point and nonlinear spring elements was constructed. The model can consider nonlinearity and positions of rubber bearings and rocking motion of the building. As a result of seismic response analysis, the nonlinearity and the rocking motion gave negative effect on the isolation performance.

INTRODUCTION

The application of seismic isolation technology to next generation light-water reactors and fast bleeder reactors has been considered in order to decline seismic force, in recent years. Moreover a seismic isolated office building in the Fukushima Dai-ichi nuclear power plant demonstrated a significant effect in the great east Japan earthquake in 2011. On the other hand, nuclear power plants have been struck by very large earthquakes recently, and further improvement in seismic reliability has required. Therefore seismic response analysis techniques for isolated buildings against very large earthquake have been required. These kinds of techniques are also effective against probabilistic assessment.

Rubber bearings are usually used as isolation devices. Generally, the rubber bearings deform linearly and have linear stiffness against seismic load in both horizontal and vertical direction. However, hardening in the horizontal direction and softening in the vertical direction occur in case of large deformation. Moreover the horizontal hardening properties depend on vertical load. However there are few investigations that consider these nonlinearities of rubber bearings.

Seismic response analysis models considering nonlinearities of rubber bearings have been proposed by the authors in the previous SMiRT 21 and 22 (2011, 2013). As a result of previous research, bad influences by nonlinearities of rubber bearings on seismic response were confirmed. In this paper, the rocking motion of isolated buildings are newly considered in order to improve the accuracy of the seismic response analyses. Influence of rocking motion, positions of rubber bearings and a position of the center of gravity into response of the isolated building are investigated.

ANALYSIS PROCEDURE

Isolated Reactor Building Model

The isolated reactor building model for analysis and its parameters are shown in Fig. 1 and table 1. The specification of the seismic isolation device is shown in table 2.

In this paper, the degree of freedom is three, that is horizontal x, vertical y and rotation θ, as shown in Fig. 1. The influence of rotation motion on the isolation performance is specially focused attention on in this paper.

The reactor building is considered a rigid body. In other words, the building is modeled as an one mass point model. The stiffness of the building is large enough compared with isolation devices, so the deformation of the building itself is negligible.

The actual isolated reactor buildings will be isolated by hundreds of isolation devices, but this paper considers whole isolation system as a model of seven groups of rubber bearings and oil dampers. This is because this paper investigates the influence of the layout of the isolation devices. Each group of isolation device consists of rubber bearings and oil dampers. In horizontal direction, both rubber bearings and oil dampers operate, and oil dampers have high damping ratio in order to suppress the response displacement. In vertical direction, only rubber bearings operate and oil dampers do not work, because their deformation is small. Moreover the vertical natural period, 1/8 seconds, was set relatively long compared with conventional isolated building by thickening rubber of the rubber bearings. The reason is to avoid isolation period from natural period of the important equipment in the building.

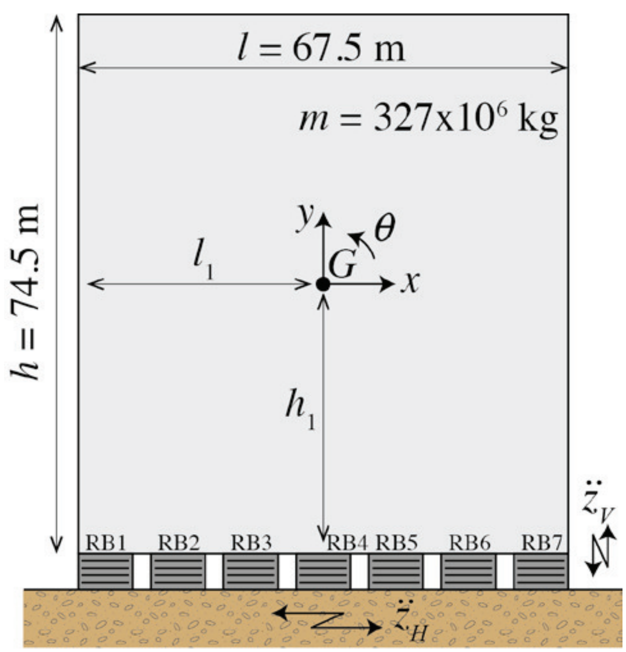


Figure 1. Analytical model of isolated reactor building.

Table 1: Parameters of analytical model of isolated building.

	Caption	
m [kg]	Mass of isolated building	327×10^6
l [m]	Width of isolated building	67.5
h [m]	Height of isolated building	74.5

Table 2: Parameters of analytical model of seismic isolation.

	Caption		
T_H [s]	Natural period	Horizontal	3.4
T_V [s]		Vertical	1/8
ζ_H [%]	Damping Ratio	Horizontal	45
ζ_V [%]		Vertical	2

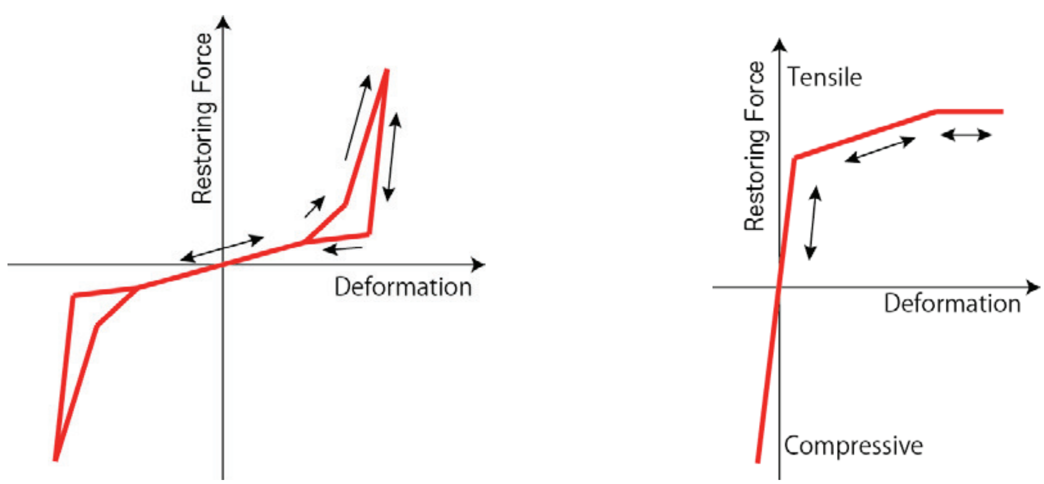
Restoring Force Model of Rubber Bearing

Generally, the rubber bearings deform linearly and have linear stiffness against seismic load in both horizontal and vertical direction. However, Fujita et al. (1988) showed that rubber bearings have hardening in the horizontal direction and softening in the vertical direction occur in case of large deformation, and Katoh et al. (1993) proposed their analysis models as shown in Fig. 2.

The hardening in horizontal direction is caused by the strain hardening of rubber material. In addition, the hardening starting deformation depends on the maximum deformation that the rubber bearing experiences and the vertical load. In the design criteria of Japan, the rubber bearings must maintain its linearity more than 1.5 times of the design deformation.

The softening in vertical direction is caused by a characteristic difference of rubber bearings between compression and tension. Therefore the softening occurs when the vertical load exceeds the weight of the upper structure.

These nonlinearities in detail were reported by the previous paper by authors (2013).

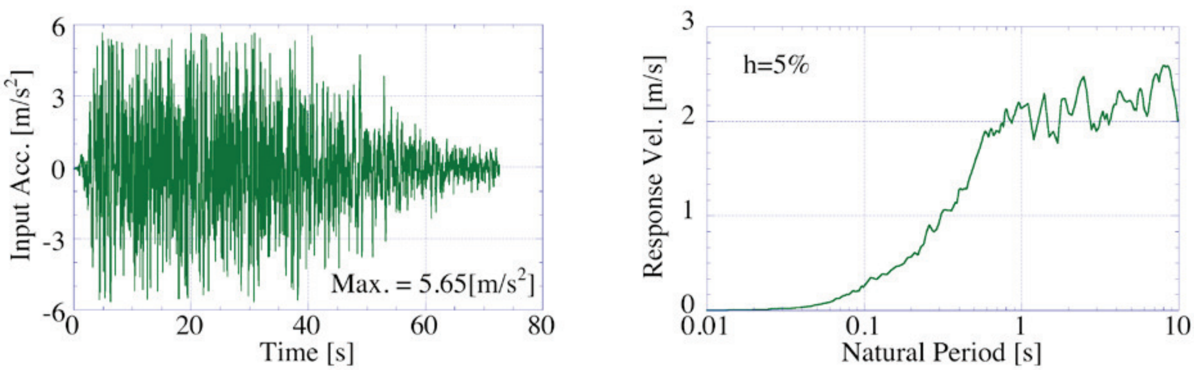


(a) Horizontal (b) Vertical

Figure 2. Restoring force characteristics of rubber bearings.

Input Wave

In this study, an artificial seismic wave was used as input wave. Figure 3 shows the time history and the velocity response spectrum. This wave was made in consideration of a target spectrum of design basis earthquake ground motion. A wave of which amplitude is 2/3 of the wave for horizontal direction is used for vertical direction. Amplitude of the wave is varied in analyses in order to investigate relationships between response and earthquake level.



(a) Time history (b) Velocity response spectrum

Figure 3. Restoring force characteristics of rubber bearings.

Table 3: Analytical condition for investigation regarding rocking motion.

Condition	Rocking	Nonlinearities	Evaluation point
1	x	x	Center of gravity
2	○	x	Center of gravity
3	x	○	Center of gravity
4	○	○	Center of gravity
5	○	○	Bottom right corner

INFLUENCE OF ROCKING MOTION

Simulation analyses were carried out in order to investigate influence of rocking motion on response.
Table 3 shows the analysis conditions. The condition 1 considers neither rocking motion nor nonlinearities. The condition 2 considers rocking motion, but it doesn't consider nonlinearities. The condition 3 doesn't consider rocking motion, but it considers nonlinearities. The conditions 4 and 5 consider both rocking motion and nonlinearities. In addition, conditions 1, 2, 3 and 4 evaluate response of the gravity center, and the condition 5 evaluates response of the bottom right corner of the building.
Figure 4 shows relationships between the maximum input acceleration and the maximum response acceleration of the center of gravity on the horizontal direction.
At first, influence of rocking motion in linear system is investigated by using the conditions 1 and 2. As shown in Fig. 4, both results are equivalent to each other, so there is few influence of rocking motion on response.
Next, influence of rocking motion in nonlinear system is investigated by using the conditions 3 and 4. The response of the isolated building that considers nonlinearities of rubber bearings is larger than the

linear system, when the input earthquake is larger than design level. In addition, the response considering rocking motion is larger than response that does not consider rocking motion, when input earthquake is more than 3 times of the design level.

Finally, influence of the evaluation point is investigated by using the conditions 4 and 5. The response at the bottom right corner is more than twice as large as the response at the center of gravity, because of the rocking motion. Therefore equipment installed at far from the center of gravity is exposed to severe seismic condition.

Consequently, nonlinearities of rubber bearing and the rocking motion of isolated buildings increase response of the isolated building, when input earthquake is large.

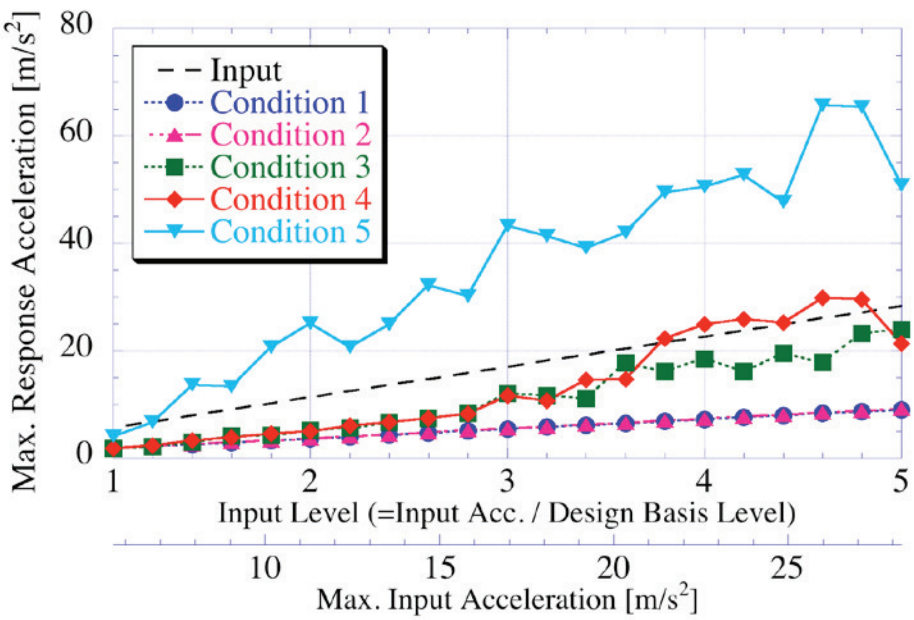
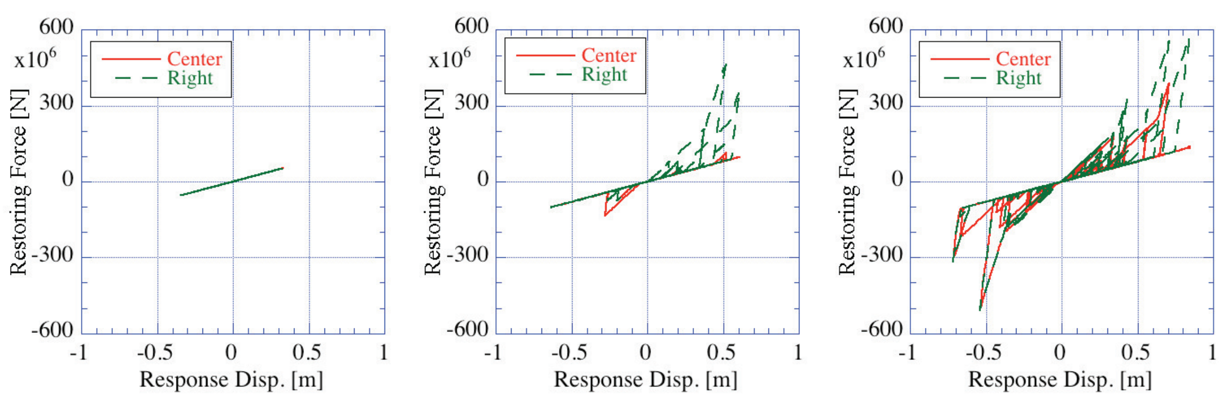


Figure 4. Influence of rocking motion.
(Horizontal, center of gravity)



(a) Design basis x 1.0 (b) Design basis x 2.0 (c) Design basis x 3.0

Figure 5. Comparison by position of rubber bearings.
(Horizontal, RB4 and RB7)

COMPARISON BY POSITIONS OF RUBBER BEARINGS

In order to compare the behavior of the rubber bearings by their positions, Fig. 5 shows the comparison of the hysteresis loops on horizontal direction between the rubber bearings installed in center and right side, that is *RB4* and *RB7* of Fig. 1. Figure 5 consists of graphs of three different input amplitude.
As shown in Fig. 5 (a), the rubber bearings deformed linearly in design basis level, and the deformations are equivalent to the other. However the restoring force of the rubber bearing installed in right side is larger than it of center, when rubber bearings deform nonlinearly, as shown in Fig. 5 (b) and (c). This is because the hardening properties of horizontal direction depend on vertical load, then the rubber bearing of right side is affected by rocking motion compared with the it of center.
As a result, it was confirmed that the rubber bearings of both ends are severe as compared with center, when input earthquake is large.

COMPARISON BY CENTER OF GRAVITY

Simulation analyses were carried out in order to investigate influence of positions of the center of gravity of the isolated building on response.
Figure 6 and table 3 show the positions of the center of gravity of the isolated building. In the position 1, the center of gravity is in the centroid of the isolated building. In the position 2, the center of gravity is in

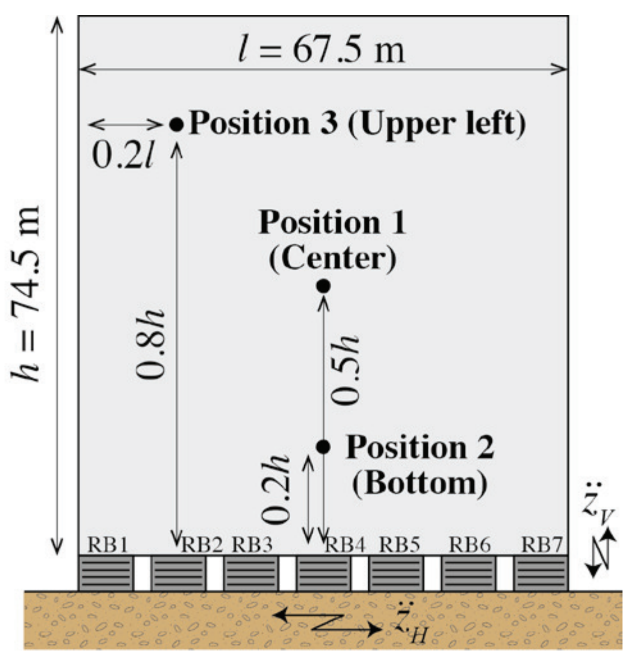


Figure 6. Position of center of gravity.

Table 4: Analytical condition for investigation regarding center of gravity.

Position	l_1 [m] (length from left side)	h_1 [m] (length from bottom)
1 (Center)	0.5 *l*	0.5 *h*
2 (Bottom center)	0.5 *l*	0.2 *h*
3 (Upper left)	0.2 *l*	0.8 *h*

the bottom of the isolated building. In the position 3, the center of gravity is in the upper left of the isolated building.

Figure 7 shows relationships between the maximum input acceleration and the maximum response acceleration of the center of gravity on the horizontal direction. As shown in Fig. 7, when the input earthquake is less than 2.4 times of the design level, response is equivalent to each other, and it increases linearly according to the increase of the input level. However, when the input earthquake is more than 2.4 times of the design level, the response varied, and the response acceleration increases more. The reason is that nonlinear behaviors of the rubber bearings raised the response of the isolated building.

Figure 8 shows relationships between the maximum input acceleration and the maximum deformation of the rubber bearing installed in the right end of the building, that is RB7, on the horizontal direction. As shown in Fig. 8, when the input earthquake is less than 2.2 times of the design level, the maximum deformation of the rubber bearing is equivalent to each other, and it increases linearly according to the increase of the input level. However, when the input earthquake is more than 2.2 times of the design level, the maximum deformation varied, and it converged. This is because the hardening effect of rubber bearings suppresses excessive deformation.

In the Figs. 7 and 8, horizontal response acceleration of the building and deformation of the rubber bearing of the building which has the center of gravity in the upper left were smaller. The imbalance of center of gravity caused rocking motion, thereby reducing the horizontal response.

CONCLUSION

In this paper, the seismic response analysis model, that can consider nonlinearities of rubber bearings and the rocking motion of isolated buildings, was proposed in order to improve the accuracy of simulation. Then influence of rocking motion, positions of rubber bearings and a position of the center of gravity into response of the isolated building were investigated. The results are summarized as follows.

Nonlinearities of rubber bearing and the rocking motion of isolated buildings increase response of the isolated building, when input earthquake is large.

Rubber bearings that are installed in both ends are severe as compared with rubber bearings of the center, when input earthquake is large.

Differences of response between positions of the center of gravity appears, when input earthquake is large.

ACKNOWLEDGEMENT

The authors would like to express his appreciations to Mr. Naoki AKAMATSU and Mr. Sebastien CHIREZ of graduate school of Tokyo Denki University for his devoted assistance.

REFERENCES

Minagawa, K., Fujita, S., Yamaguchi, A., Takata, T., Kurisaka, K. (2011). "Development of Level-1 PSA Method Applicable to Japan Sodium-cooled Fast Reactor: (2) Seismic Response Analysis Considering Characteristics of the Advanced Seismic", *Transactions of SMiRT 21*, p263.pdf.

Minagawa, K., Fujita, S., Yamaguchi, A., Takata, T., Kurisaka, K. (2013). "Seismic Response Analysis of Isolation System Considering Coupling Effect between Horizontal and Vertical Deformation of Rubber Bearings", *Transactions of SMiRT 22*, Pap_737_ver_1.pdf.

Fujita, T., Fujita, S., Suzuki, S., Yoshizawa, T. (1988). "An Experimental Study of Laminated Rubber Bearings for Earthquake Isolation of Buildings : 3rd Report, Breaking Tests for Rubber Bearings of 980-kN Rated Load", *Transactions of the Japan Society of Mechanical Engineers*, C 54(507), 2618-2623, [in Japanese].

Katoh, A., Nagura, S., Nojima, O., Yoneda, G. (1993). "Study on concept of seismic isolation type plant for FBR: Part 28 Ultimate Behavior of Base-Isolated Reactor Building (Sensitivity Analysis on

Hysteresis Curve Modeling Method)", *Proceedings of Architectural Institute of Japan*, 1595-1596, [in Japanese].

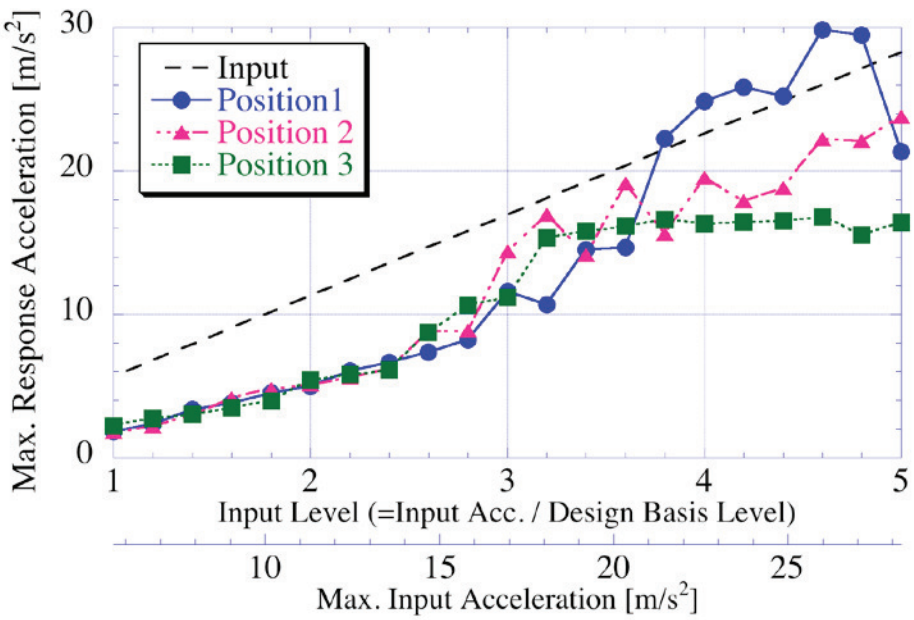


Figure 7. Comparison of response of isolated building by position of center of gravity.
(Horizontal, center of gravity)

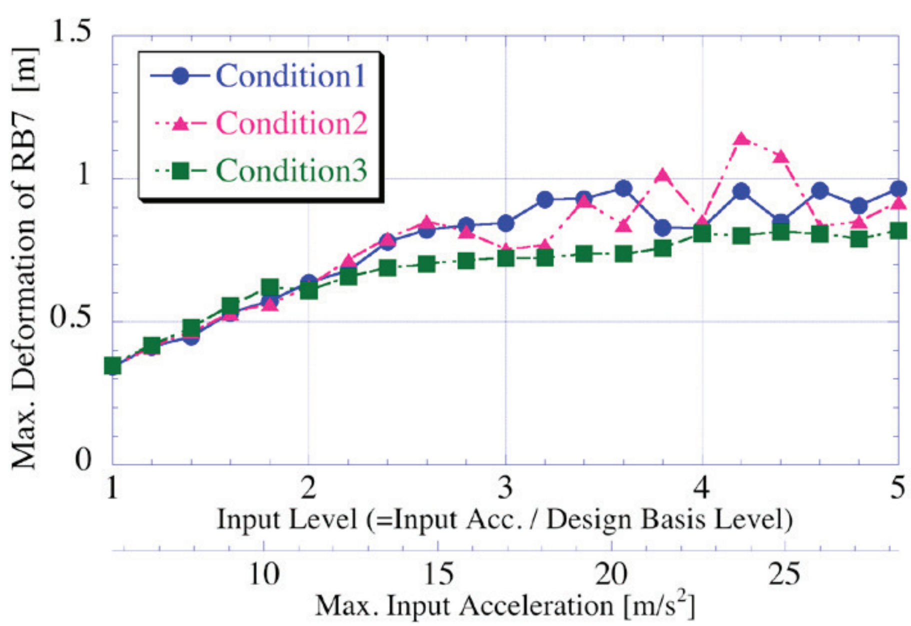


Figure 8. Comparison of deformation of rubber bearing by position of center of gravity.
(Horizontal, RB7)