AN EXPERIMENTAL STUDY ON THE ROTATIONAL AND VERTICAL LOAD-CARRYING CHARACTERISTICS OF RUBBER BEARINGS

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SUMMARY

The load-carrying characteristics of rubber bearings having no rotation at the top and bottom ends have been well studied for isolated buildings. But, the serviceable and profitable way to reduce building costs is to install rubber bearings into columns at an intermediate height. This method makes it easy to retrofit existing buildings. For this application, however, it is necessary to clarify the rotational and vertical characteristics of rubber bearings installed into columns at an intermediate height and to explain the influence of rotation on shear deformation characteristics. The load-carrying characteristics of rubber bearings under the shear deformation, rotation and axial deformation were examined by experimental studies. And correlations among the characteristics were clarified. Furthermore, it was also found that the rotational and horizontal characteristics of rubber bearings could be accurately represented by the theoretical way in the elastic range.

INTRODUCTION

The load-carrying characteristics of rubber bearings having no rotation at the top and bottom ends have been well studied for isolated buildings. In fact, most isolated buildings in Japan have been designed to satisfy the simple stress conditions for rubber bearings using the installation of high-stiffened beams to the top and bottom ends of rubber bearings. Another serviceable and profitable way to reduce building costs is to install rubber bearings into columns at an intermediate height. This method makes it easy to retrofit existing buildings that are not seismically sound. For this application, however, it is necessary to clarify the rotational and vertical characteristics of rubber bearings installed into columns at an intermediate height and to explain the influence of rotation on shear deformation characteristics.

Hence, a series of static loading tests for rubber bearings was performed to meet the above objectives. This paper represents the obtained results and some consideration with the Haringx's theory.

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OUTLINE OF THE TESTS

Test Device

The outline of the test device is shown in Figure 1. It is designed for rubber bearings from ϕ300 to ϕ400 size. A rubber bearing is clamped at the bottom face. And the horizontal displacement, vertical force and rotation are simultaneously acted at the top face. The features of the device are as follows:

- Two vertical oil jacks (whose stroke is ±100mm) and a horizontal oil jack (whose stroke is ±400mm) are used.

Those jacks are pin-connected at the both ends.
It enables to rotate the top of rubber bearings by two vertical jacks.
The horizontal force, vertical force and bending moments acted at the top of rubber bearings are calculated, considering the angles of three jacks.
In the tests, the horizontal displacement, vertical force and rotation are arbitrarily acted by those incremental values obtained from the iterative method using personal computer control.

Specimen of the Tested Rubber Bearing

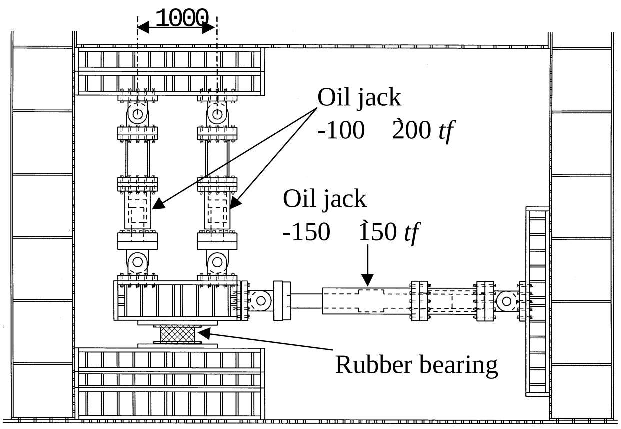
There are two tested rubber bearings whose sizes are ϕ300. One has a lead plug in the center hole of rubber bearings. The other has no lead plugs. The cross section of the rubber bearing is illustrated in Figure 2. The rubber bearing consists of 24-rubber-sheet whose thickness is 2.4*mm* and 23-steel-plate whose thickness is 2.5*mm*. The total height is 62.4*mm*. The shear elastic modulus *G* of the rubber sheets is 6 kgf/cm^2.

Series of Test

The following tests are carried out to confirm the load-carrying characteristics of rubber bearings subject to rotation for the case installed rubber bearings into columns at an intermediate height.

(A) Rotational performance tests under the constant shear strain and vertical forces.
(B) Vertical performance tests under the constant shear strain and no rotation.
(C) Horizontal performance tests under the constant vertical force and no rotation.
(D) Horizontal performance tests under the varying vertical force and no rotation.
(E) Horizontal performance tests under the constant vertical force and varying rotation.
(F) Horizontal performance tests under the varying vertical force and varying rotation.

In order to check basic characteristics of rubber bearings subject to rotation at the top face, Test (A) is carried out. Similar to Test (A), Test (B) is planed for the vertical stiffness of rubber bearings. Test (C), (D), (E) and (F) are conducted to check the effects of the vertical force and rotation to the horizontal stiffness. And, those tests correspond to the rubber bearing under the inside columns and beams, under the outside columns and beams, at the top or bottom of the inside column and at the top or bottom of the outside column, respectively.



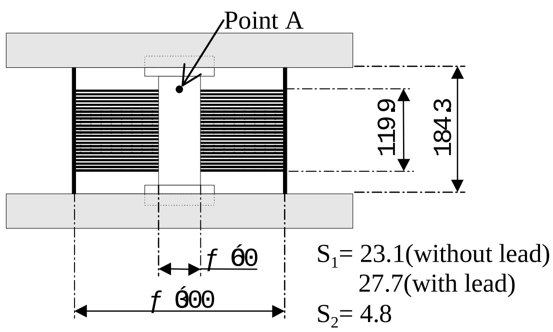


Figure 1: Outline of the test device. **Figure 2: The shape of a tested rubber bearing.**

RESULTS OF THE TESTS

Rotational Performance Tests

The loading schedule of rotational performance tests are shown in Table 1. The symbol "~" in the table denotes the continuously varying values. In the tests, rotation angle at the top of rubber bearings is varied continuously under the condition which the shear deformation and the axial force are constant. The main aim at this test is to clarify the influence of shear deformation and axial force to the rotational stiffness of rubber bearings.

Table 1: The loading schedule for rotational performance tests.

Shear strain (%)	Mean vertical pressure (kgf/cm^2)	Rotation angle (*radian*)	The number of times
0	0,10,20,30,40,50,100,150	-1/50~+1/50	2
+10	50,100,150	-1/50~+1/50	2
-20	50,100,150	-1/50~+1/50	2
+50	50,100,150	-1/50~+1/50	2
-100	50,100,150	-1/50~+1/50	2
+150	50,100,150	-1/50~+1/50	2

The relationship between rotation angles and bending moments at the top of rubber bearings, as shown at the point A in Figure 2, is partially represented by Figure 3. The gradient in the figure indicates the rotational stiffness of rubber bearings.

The relationship between the rotation angle and axial force, and the relationship between the rotational stiffness and shear deformation are represented in Figure 4 and 5, respectively. The theoretical values $K_R = E_{rb}/T_R$ (E_{rb} : Apparent longitudinal Young's modulus for bending deformation obtained from volume elastic modulus, I : Moment of inertia, T_R : Total thickness) are also plotted in Figure 4. For this calculation, the shear elastic modulus $G=6\ kgf/cm^2$ and volume modulus $E_b=20000\ kgf/cm^2$ are used.

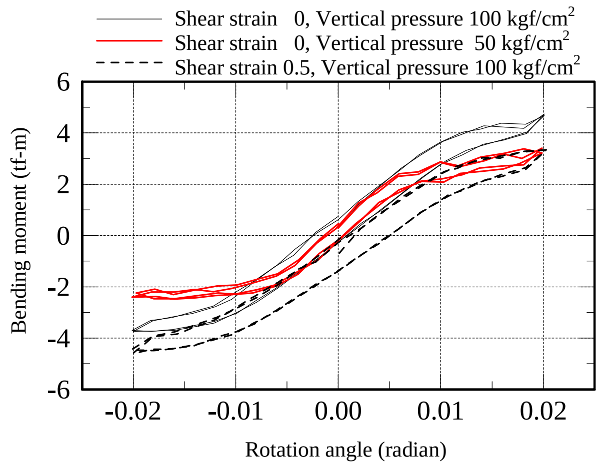


Figure 3: The relationship between the rotation angle and bending moment at the top of rubber bearings in the case without lead plugs.

Results of rotational performance tests are as follows:

- The rotational stiffness of rubber bearings with the lead plug is generally larger than that without lead. The influence of the axial force for rubber bearings with lead is smaller than that without lead.
- When the shear deformation is zero, the rotational stiffness is largest at the mean vertical pressure of 30 kgf/cm^2. Because, some parts of the rubber bearing become to be tensile condition when the axial force is small.

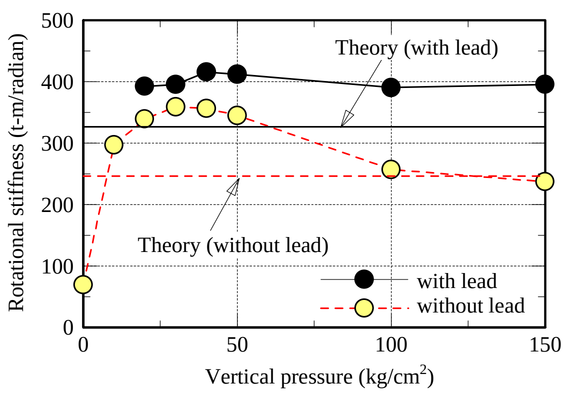


Figure 4: The relationship between the rotational stiffness and the vertical pressure of rubber bearings when the shear strain is zero.

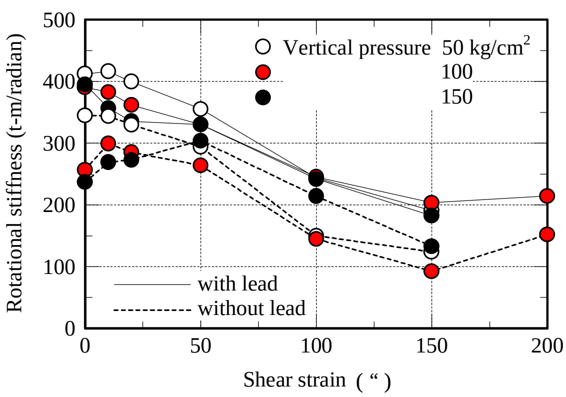


Figure 5: The relationship between the rotational stiffness and the shear strain of rubber bearings.

- The theoretical values of the rotational stiffness are about 30% smaller than the measured maximum values.
- The rotational stiffness becomes smaller as the shear strain is large.

Vertical Performance Tests

In the vertical performance tests, the vertical stiffness of rubber bearings is examined under the constant shear strain without rotation at the top of rubber bearings. The results of the relationship between the vertical stiffness and the shear strain are represented in Figure 6. In the figure, the theoretical values obtained by Fujita and Iizuka are also represented. The both theoretical values are set to be equivalent to measured ones at the shear strain of 0%.

Considerations for vertical performance tests are as follows:

- The vertical stiffness by Fujita, which is proportional to the effective support area of rubber bearings, becomes smaller than the results of the tests as the shear strain increases.
- When the shear strain is smaller than 120%, the vertical stiffness by the tests is smaller than the theoretical values by Iizuka. On the other hand, when the shear strain is larger than 120%, the vertical stiffness by the tests is larger than the theoretical values.

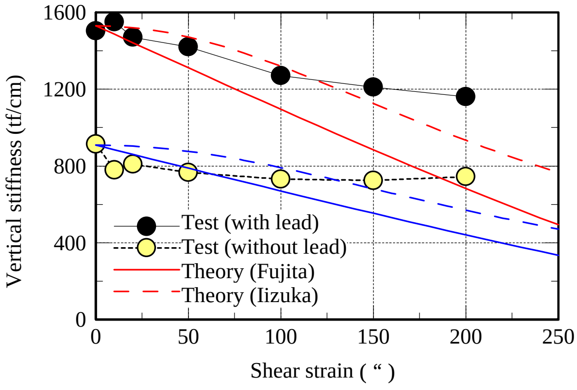


Figure 6: The relationship between the vertical stiffness and the shear strain of rubber bearings.

Horizontal Performance Tests under Various Stress Conditions

The loading schedules of the horizontal performance tests including Test (C), (D), (E) and (F) are shown by Table 2. The symbol “~” in the table denotes the continuously varying values. When the shear strain of rubber bearings is zero, the mean vertical pressure and rotation angle are set to be 100 *kgf/cm*^{2} and 0 *radian*, respectively. And, when the shear strain comes to the maximum value, the vertical pressure and rotation angle come to maximum values. For the reverse direction, those values take minimum.

The maximum value of the rotation angle produced at the top of rubber bearings is planned to be 1/100 *radian* since the maximum value of rotation is about 1/100 *radian* for the ordinary hinges of the columns. Though the rotation angle is large for the small amplitude of shear strain, but authors took the easiness for comparison.

Table 2: The loading schedules for horizontal performance tests under various stress conditions

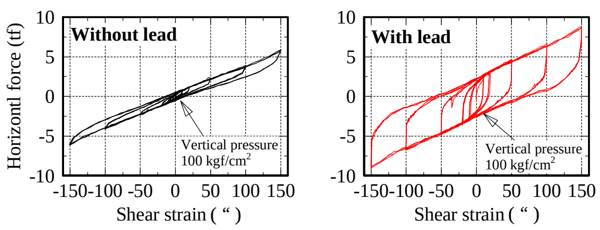
Test name	Shear strain (%)	Vertical pressure (*kgf/cm*^{2})	Rotation angle (*radian*)	The number of times
Test (C)	-100~+100	100	0	3
Test (D)	-10~+10	50~150	0	3
	-20~+20	50~150	0	3
	-50~+50	50~150	0	3
	-100~+100	50~150	0	3
	-150~+150	50~150	0	3
Test (E)	-10~+10	100	-1/100~+1/100	3
	-20~+20	100	-1/100~+1/100	3
	-50~+50	100	-1/100~+1/100	3
	-100~+100	100	-1/100~+1/100	3
	-150~+150	100	-1/100~+1/100	3
Test (F)	-10~+10	50~150	-1/100~+1/100	3
	-20~+20	50~150	-1/100~+1/100	3
	-50~+50	50~150	-1/100~+1/100	3
	-100~+100	50~150	-1/100~+1/100	3
	-150~+150	50~150	-1/100~+1/100	3

In the case of Test (F), the test results are compared with the Haringx’s theory. The bending stiffness S_b and horizontal stiffness S_s for the Haringx's theory are obtained from the basic performance tests. S_b comes from the rotational performance tests when the shear strain is 0% and the mean vertical pressure is 50 kgf/cm^2. And, S_s comes from the horizontal performance tests when the shear strain is 100%, the mean vertical pressure is 50 kg/cm^2 and no rotation. S_b and S_s are 4.17×10^5 $tf \cdot cm^2$ and 7.19 *tf*, respectively. In the Haringx's theory, those two stiffness are used as linear values. The horizontal force and bending moment at the end of rubber bearings for the Test (F) are calculated from the theory.

The results of Test (D), (E) and (F) are represented in Figure 7, 8 and 9, respectively. These figures show the comparison of the relationship between the horizontal force and horizontal displacement, and the relationship between the bending moment and rotation angle at the top face. And, the horizontal stiffness and the equivalent viscous damping factor, at the shear strain of 100 % and the vertical pressure of 100 kgf/cm^2, are listed by Table 3. For the case of Test (F), the calculated values using the Haringx's theory are plotted in Figure 10, which corresponds to Figure 9.

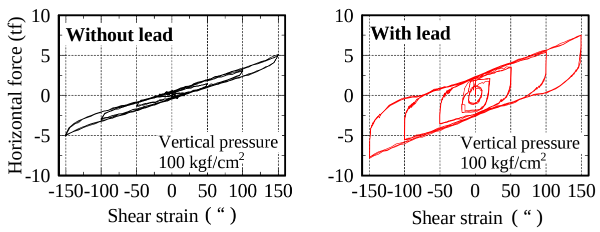
Table 3: The list of horizontal performance tests results

Test name		Test (C)	Test (D)	Test (E)	Test (F)
With lead	Horizontal stiffness after yield (*tf/cm*)	0.62	0.56	0.41	0.43
	Equivalent horizontal stiffness (*tf/cm*)	0.68	0.62	0.48	0.50
	Equivalent viscous danping (%)	5.3	6.1	7.5	7.2
Without lead	Horizontal stiffness after yield (*tf/cm*)	0.70	0.59	0.49	0.54
	Equivalent horizontal stiffness (*tf/cm*)	1.04	0.96	0.87	0.90
	Equivalent viscous danping (%)	21.2	24.3	26.6	25.4

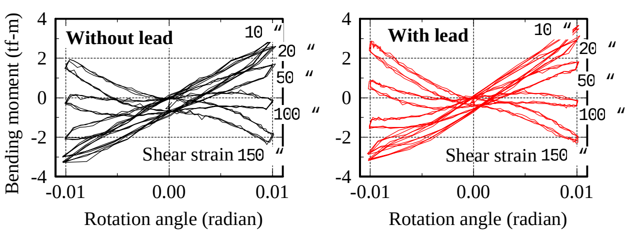


(a) The relationship between the horizontal force and shear strain

Figure 7: The results of Test (D)

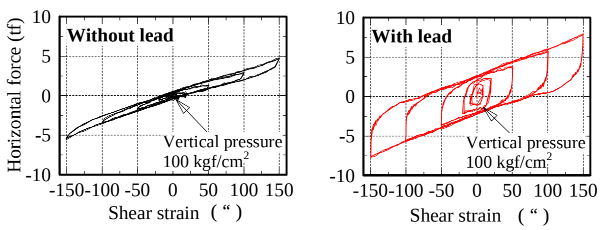


(a) The relationship between the horizontal force and shear strain

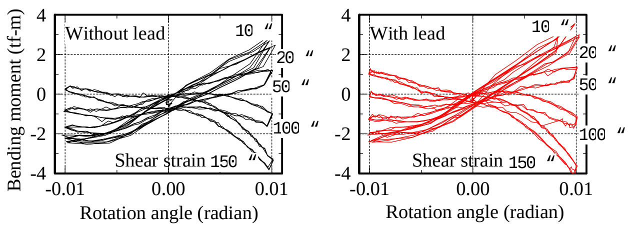


(b) The relationship between the bending moment and rotation angle

Figure 8: The results of Test (E)



(a) The relationship between the horizontal force and shear strain



(b) The relationship between the bending moment and rotation angle

Figure 9: The results of Test (F)

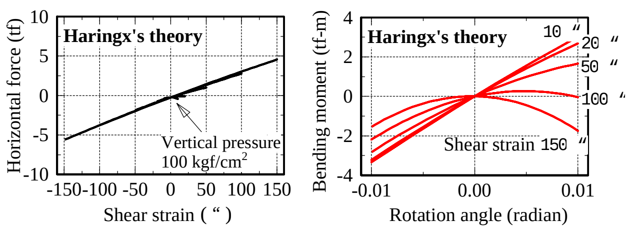


Figure 10: Calculated values by the Haringx's theory corresponding to Test (F)

Results and considerations of horizontal performance tests are as follows:

For Test (D) under the varying vertical force and no rotation.

- The horizontal stiffness after the yield for Test (D) is slightly smaller than it of Test (C) as shown in Table 3. It is recognized that the influence on the variation of the vertical pressure is small.
- The equivalent viscous damping factor in Table 3 of Test (D) is slightly larger than that of Test (C).

For Test (E) under the constant vertical force and varying rotation.

- The horizontal stiffness of Test (E) is remarkably reduced to 70% of the horizontal stiffness of Test (C), by the rotation at the top face of rubber bearings.
- The negative horizontal stiffness is produced when the shear strain is smaller than 20%. Because, the shear force is generated to the reverse direction by the rotation. However, the ratio of negative shear force to positive shear force decreases as the shear strain increases, because the negative shear force is constant as the rotation angle is constant.

For Test (F) under the varying vertical force and varying rotation.

- The results of Test (F) have the composed characteristics of those of Test (D) and (E) by roughly estimation.
- The horizontal stiffness of rubber bearings is remarkably reduced when the large compressive vertical force is acted.
- The rotational stiffness in the low vertical pressure of Test (F) is different from the Haringx's theory because of non-linear characteristics in tension condition of the rubber. But, the Haringx's theory indicates good agreement with the results of the Test (F) within the elastic range.

CONCLUSION

The static loading tests of rubber bearings were carried out in order to examine the influence of the rotation at the top and bottom face against usual load-carrying characteristics. The rotational performance tests, the vertical performance tests and the horizontal performance tests are conducted under various stress conditions. Through those tests, the following information is obtained:

- The rotational stiffness of rubber bearings without the shear strain has a peak point when the mean vertical pressure is about $30\ kgf/cm^2$.
- The rotational stiffness becomes smaller as the shear strain increases. This reducing ratio for the rotational stiffness is larger than that for the vertical stiffness.
- The horizontal stiffness is reduced by the rotation at the ends of rubber bearings. As the natural consequence, the buckling loads decrease. On the contrary, equivalent viscous damping factor is slightly increased by the rotation.

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