Research, Development and Implementation of Rubber Bearings for Seismic Isolation

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This paper summarizes the results of research and development of rubber bearings for seismic isolation carried out by the Institute of Industrial Science, University of Tokyo and Bridgestone Corporation. A series of static tests has been carried out for normal types of rubber bearings of rated loads of 98 kN, 490 kN, 980 kN and 2 450 kN. Fundamental characteristics of the rubber bearings such as horizontal and vertical stiffness and capacities of deformations have been clarified by the tests. The same types of rubber bearing have already been implemented in seven base-isolated buildings in Japan. This paper describes the static tests including the breaking tests for the rubber bearings of the 980 kN-rated load. Furthermore, this paper refers to the durability and quality control of the natural rubber bearings, and the examples of practical implementation in buildings.

Key Words: Vibration, Seismic Isolation, Rubber Bearing, Restoring Force, Stiffness, Static Test, Breaking Test, Shear and Tension/Compression

1. Introduction

In Japan, the concept of seismic isolation of buildings had been regarded as an impracticable idea until rubber bearings were developed, although some systems using other devices had been proposed for seismic isolation. Research and development of rubber bearings in Japan were conducted for application to seismic isolation, because they had rarely been used for bridge bearings or for any other uses. As the research and development revealed desirable properties of the rubber bearings, and as usefulness and the promising future of the seismic isolation technology were recognized, construction companies began research and development into seismic isolation⁽¹⁾. These days, the research and development has become very common among many construction companies and other companies, and the implementation has been progressing rapidly. So far, about twenty base-isolated buildings have been constructed.

The research and development of natural rubber

bearings by the authors was initiated in 1981⁽²⁾, which was one of the earliest uses of rubber bearings in Japan. In the development, a series of static tests was carried out for natural rubber bearings of rated loads of 98 kN, 490 kN⁽³⁾, 980 kN⁽⁴⁾ and 2 450 kN, and the biaxial breaking tests were carried out for 980 kN rubber bearings⁽⁵⁾. Through these tests, various properties of the rubber bearings were clarified and the design method was confirmed. The same type of rubber bearing has already been implemented in seven base-isolated buildings in Japan.

This paper describes results of the static tests including the breaking tests for the 980 kN rubber bearings, and refers to durability and quality control of the natural rubber bearings together with the examples of implementation.

These types of rubber bearing have already implemented to seven base-isolated buildings in Japan.

2. Stiffness and Strength of Rubber Bearings

The static tests, including the breaking tests, on natural rubber bearings of a 980 kN-rated load were carried out to investigate the characteristics of restoring forces and the breaking conditions of those whose top and bottom planes were bonded to thick plates for fixing by bolts.

2.1 Design of rubber bearings

The rubber bearings of 980 kN-rated load used for tests were designed using the formulas shown below. For a circular bearing of diameter, d_R , layer thickness, t_R , area, $A_R (= \pi d_R^2/4)$, second moment of

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area, $I(=\pi d_R^4/64)$, number of layer, n , thickness of steel plate, t_s and total height of bearing, $l(=nt_R+(n-1)t_s)$, the horizontal stiffness of rubber bearing under compression can be expressed⁽⁶⁾ as

$$K_H = P^2 / \{2qS_b \tan(q/2) - Pl\} \quad (1)$$

where

$$q = \sqrt{(P/S_b)(1+P/S_s)} \quad (2)$$

$$S_b = E'_b I (t_R + t_s) / t_R \quad (3)$$

$$S_s = GA_R (t_R + t_s) / t_R \quad (4)$$

P is the vertical load, S_b and S_s are the bending and shear stiffness of the bearing and G is the shear modulus of the rubber sheet. E'_b is the apparent compression modulus for bending considering the bulk compression and is expressed as follows,

$$E'_b = E_b E_\infty / (E_b + E_\infty) \quad (5)$$

where

$$E_b = 3G(1+2\chi S^2/3) \quad (6)$$

E_b is the apparent compression modulus for bending without considering the bulk compressibility, E_∞ is the bulk compression modulus, $S(=d_R/(4t_R))$ is the shape factor and χ is the numerical factor.

The vertical stiffness of the bearing decreases with increasing horizontal deflexion and can be expressed as

$$K_V = A_{ef} E'_c / (nt_R) \quad (7)$$

where

$$A_{ef} = \{d_R^2 \sin^{-1}(\sqrt{d_R^2 - X^2}/d_R) - X\sqrt{d_R^2 - X^2}\} / 2 \quad (8)$$

A_{ef} is the effective area, X is the horizontal displacement and E'_c is the apparent compression modulus considering the bulk compressibility which is expressed as

$$E'_c = E_c E_\infty / (E_c + E_\infty) \quad (9)$$

where E_c is the apparent compression modulus without considering the bulk compressibility.

The permissible shear strain for the bearings is checked by the following formula.

$$X / (nt_R) + 6SP / (A_{ef} E'_c) \leq \epsilon_B / 2 \quad (10)$$

This formula requires that the combined shear strains resulting from the nominal shear strain for the displacement X and the local shear strain due to com-

pression should not exceed the value defined by the 0.5 of the elongation at break ϵ_B ⁽⁷⁾.

2.2 Rubber bearings used for tests

Figure 1 shows the full-sized rubber bearing for the 980 kN-rated load. This bearing comprised of 27 natural rubber sheets, 6 mm thick and 600 mm in diameter bonded to steel plates, was designed to provide a 100 000 kg-rated mass with a horizontal natural frequency of 0.51 Hz and a vertical frequency of 21 Hz and to withstand a horizontal displacement larger than 300 mm. The natural rubber employed had the properties shown below ;

$$G = 0.58 \text{ MPa}, E_\infty = 2.03 \text{ GPa}, \epsilon_B = 6.5$$

$$\text{Hardness (IRHD)} = 40, \chi = 0.85$$

where G is the shear modulus, E_∞ is the bulk modulus, ϵ_B is the elongation at break and χ is a numerical factor depending on the amounts of carbon black filler.

The 0.4 scale models of the bearing were also used for the biaxial breaking tests.

2.3 Static tests

As shown in Fig. 2, the tests were done using test apparatus which exerted vertical loads and horizontal displacements on a pair of the bearings while keeping both end surfaces of each bearing parallel by a link mechanism. Both the horizontal-vertical displacement and restoring force of the bearing were measured. In the tests, as shown in Fig. 3, the vertical load distributions across the top plane of the bearing under

Rubber sheet : 6mm^T × 27 = 162mm

Steel plate : 3mm^T × 26 = 78mm

Fig. 1 Rubber bearing of 980 kN-rated load

Fig. 2 Test apparatus for static tests

various horizontal displacements were also measured by the five small load cells set in the steel flange (top plane); and furthermore, the tensile forces induced in the fixing bolts were measured.

Figure 4 shows the horizontal restoring forces of the bearing for displacements up to 0.3 m under various constant vertical loads, P , together with the height reductions in it measured simultaneously. The horizontal stiffness of the bearing slightly decreased with increased vertical load; under a fixed vertical load, it was roughly linear for displacement, although it softened slightly with displacement and then slightly hardened with further displacement. This nonlinear behaviour seems to imply that the material nonlinearity of the rubber causing hardening of the stiffness became dominant with displacement in contrast to the geometrical nonlinearity which caused softening.

From the results shown in Fig. 4, the vertical restoring forces of the bearing for vertical displacements (height reduction) under various fixed horizontal displacements, X , were derived as shown in Fig. 5. The vertical stiffness of the bearing decreased considerably with horizontal displacement. This relationship was caused by the decreased overlapping area of the

Fig. 3 Methods for measurements of vertical load distributions and tensile forces induced in the fixing bolts

upper and lower end planes of the laminated rubber which substantially supported the vertical load.

From the restoring force characteristics shown in Fig. 4, the horizontal stiffnesses for horizontal displacements under each vertical load and for vertical loads under several horizontal displacements were derived as shown in Fig. 6. The stiffnesses calculated were the linear equivalents generating the same elastic energies as those were defined as the integrals of the forces given by the centre lines of the restoring force loops with respect to the displacements. Figure 6 shows the horizontal stiffnesses and the natural frequencies when these bearings supported a 100 000 kg mass, with respect to the amplitude of horizontal displacement and vertical load. The horizontal stiffness was not much affected by the horizontal displacement up to the permissible displacement (0.3 m) and the vertical load up to two times the rated load (980 kN). The dotted line in Fig. 6 is derived

Fig. 4 Restoring force vs horizontal displacement, and height reduction vs horizontal displacement under various vertical loads

Fig. 5 Vertical restoring force vs vertical displacement under various fixed horizontal displacements

from Eq.(1) and agrees well with the experimental results. This means Eq.(1) is valid for designing bearings for practical use.

Figure 7 shows the vertical stiffness and the natural frequencies obtained by the same methods as those used for Fig. 5 with respect to the amplitude of vertical load and horizontal displacement. The effect of the amplitude of vertical load was negligibly small but the stiffness seems to be very much affected by the horizontal displacement. The dotted line in Fig. 7 was derived from Eq.(7) and agrees with the experimental results. The height reductions shown in Fig. 4 were also derived from Eq.(7) showing good agreement with the experimental results. Equation(7) was obtained on the assumption that the bearing supported the vertical load in the overlapping area of the upper and lower end planes of the bearing. This assumption could be proven by measuring the load distributions as follows.

Figure 8 shows the vertical load distributions across the top plane of the bearing under various horizontal displacements up to 0.3 m. The results indicate that the bearing sustains the vertical load in the overlapping area and the distributions are parabolic.

Figure 9 shows the tensile forces induced in the fixing bolts. The tensile force is induced for a displace-

ment of 0.1 m under the rated load while the value itself counts for nothing. This fact indicates that the inverse properties apply for the dowel-type bearings while they have the advantage of reducing tension loads on the bearings, because, in the case of the dowel-type bearings, the flanges of the bearings were capable of lifting even in this small displacement (0.1 m).

2.4 Breaking tests by simple tension

The breaking tests by simple tension were carried out for four full-sized rubber bearings. Figure 10 shows the test apparatus. The vertical tensile force was applied by the 9.8 MN structural testing machine (Research Institute of Science & Technology, Nihon University) up to the breaking point. The tensile force and the vertical displacement were measured.

Failure occurred in the rubber sheets bonded to one of the flanges for all cases as shown by the wave lines in Fig. 11. The breaking displacements were very large values of 0.361 m (breaking strain is 223 %) to 0.595 m (367 %) as shown in Fig. 12. Also, the breaking forces were 1 145 kN to 1 894 kN which corresponded to the values from 1.17 to 1.93 times the rated load (980 kN). This fact indicates that the bearings would not break even if the isolated buildings were suspended by the bearings used for isolating them.

Fig. 6 Horizontal stiffness vs amplitude of horizontal displacement and vertical load

Fig. 7 Vertical stiffness vs amplitude of vertical load and horizontal displacement

Fig. 8 Vertical load distributions

Fig. 9 Tensile force induced in the fixing bolts

2.5 Biaxial breaking tests by tension and shear

The biaxial breaking tests by tension and shear were done by using 9 pairs of 0.4 scale bearing models. The set up is shown in Fig. 13. The vertical tensile force was applied by the hydraulic cylinder suspended from the 3-dimensional loading frame at Chiba Experiment Station, Institute of Industrial Science, University of Tokyo, under three pre-shear strains of 0%, 185% and 309% which were produced by the hydraulic cylinder between the bearings. The 185% shear strains correspond to the permissible deflexion 0.3 m in a full-sized bearing. Figure 14 shows the tensile breaking characteristics of the bearings under 185% and 309% pre shear strains. The results showed that, though breaking tensile forces decreased with increased shear deflexions, the breaking forces were still large (0.80 to 0.94 times the rated load) even under a shear deflexion of 0.3 m in full size. Figure 15 shows the state just before breaking.

Fig. 10 Test apparatus for breaking test by simple tension

2.6 Biaxial breaking tests by compression and shear

As shown in Fig. 16, the biaxial breaking tests by compression and shear for 6 pairs of 0.4 scale models were carried out by using the same type of test apparatus as that used for the static tests previously mentioned. The vertical load, which ranged up to 313.6 kN (two times the rated load) was produced by the 1.96 MN structural testing machine and the horizontal load was given by the large capacity hydraulic cylinder until the bearings broke.

Figure 17 shows the shear breaking characteristics of the bearings under the rated load and the two times that load. The results revealed that the breaking

shear strains were almost constant under various vertical loads up to 2 times the rated load and they were about 500%, corresponding to a shear deflexion

Fig. 11 Breaking characteristics by simple tension for the full-sized rubber bearings

State Just Before Breaking

Breaking tensile force
1,894 kN
Breaking tensile displacement
0.595 m
Breaking tensile strain
367 %

Fig. 12 Breaking test by simple tension for the 980 kN rubber bearings (full size)

Fig. 13 Test apparatus for biaxial breaking test by tension and shear

of 0.8 m in full size which was larger than the diameter of the bearing, and the breaking shear forces were 1.6 or 1.7 times the rated load. This result is contrary to the assumption that the bearing supports the vertical load in the overlapping area of the top and bottom plane. However, it was observed that the local deformation of rubber occurred at the both end planes to increase the effective area to support the vertical load as shown in Fig. 18.

All the results obtained by the breaking tests were arranged into a graph which revealed tensile/compressive stress with respect shear deflexion, as shown in Fig. 19. The dotted line connects the average values of the results for several tests mentioned before. The results revealed that the bearings would

not break as long as they were used in the area of stress-strain indicated to the left of the dotted line.

3. Durability and Quality Control

Since creep under compressive loads is usually regarded as an undesirable effect in rubber bearings, natural rubber is one of the best materials used for the bearings because it has excellent anti creep characteristics. However, natural rubbers, in general, have some weak points in agents of atmosphere such as ozone, oxygen and light.

To avoid the detrimental effects of these agents, Bridgestone Corporation has developed a rubber bearing protected by a surface synthetic rubber, as shown in Fig. 20. Although the effects of these agents are usually confined to the surface, the inner rubber is also slightly affected, as shown in Fig. 21 and Fig. 22. For general base-isolated buildings, bearings are designed to have adequate properties for the protection of buildings from the site-dependent earthquake input

Fig. 14 Breaking characteristics by tension and shear for the 0.4 scale models of bearings

State just before breaking
(Pre shear strain: 185 %)

Breaking tensile force
148(925) kN

Breaking tensile displacement
0.138(0.345) m

Fig. 15 Biaxial breaking test by tension and shear for 0.4 scale models of the 980 kN rubber bearing

Fig. 16 Test apparatus for biaxial breaking test by compression and shear

Fig. 17 Breaking characteristics by compression and shear for the 0.4 scale models of bearing

for earthquake-resistant design considering the state after 60 years of use of the bearings where the various properties of the bearings are predicted by the accelerated tests provided by JIS K 6301-1975 (Japanese Industrial Standard, Physical Testing Methods for Vulcanized Rubber).

However, considering the durability and reliability of rubber bearings have been demonstrated for over many years, as an example, the bridge bearings used for the Pelham Bridge (England) have been installed since 1956 and as these bearings have no protection from the effects of the environment previously described, it can be considered that there are basically no problems in the use of natural rubber bearings. In addition, if the bearings should suffer any damage by any chance, the re-installation of the bearings can be easily under taken.

Quality control of rubber bearings manufactured is also an important matter, especially for the bearings being used for nuclear facilities. Presently, quality controls are performed at each step of the manufacturing process and in the case of the bearings for nuclear facilities, stricter quality control methods are now being discussed. For the inspection of the bearings being used for nuclear facilities, all bearings manufactured should be tested under the deflexions fixed by the S_2 earthquake input for earthquake resistant design and under yet greater deflexions.

4. Examples of Implementation

In Japan, although it has been two or three years since the earthquake isolation of buildings was first utilized, twenty or more base-isolated buildings have already been constructed. Examples of implementation of the same type as the bearing discussed in this paper are shown in Table 1. In the case of the early imple-

State just before breaking

Breaking shear force
281 (1,756) kN

Breaking shear displacement
0.3 (0.75) m

Fig. 18 Biaxial breaking tests by compression and shear for 0.4 scale models of the 980 kN rubber bearing

Fig. 19 Breaking boundary for the rubber bearing of 980 kN-rated load

mentations, almost all of the base-isolated buildings were constructed for research purposes by the companies concerned. However, it is obvious that base-isolated buildings constructed for practical use are increasing. Figure 23 shows an example of implementation of the isolation system which consists of rubber bearings and elasto plastic dampers.

5. Conclusions

The fundamental characteristics of rubber bearings for seismic isolation such as the horizontal and

Fig. 20 Structure of rubber bearing protected from destructive agents of atmosphere by surface rubber

Fig. 21 Ozone crack in both surface and inner rubber

Fig. 22 Effect of oxygen on elongation at break for both surface and inner rubber

vertical stiffnesses and the capacities of deformations were investigated by static tests and biaxial breaking tests. In consequence, these fundamental characteristics have been clarified and the same types of the bearing have already been implemented in seven base-isolated buildings in Japan. In the near future, seismic isolation technology for entire buildings must become an indispensable factor for many industrial facilities which contain a lot of high technology-oriented equipment sensitive to earthquake, because this kind of equipment does not satisfy earthquake resistance requirements by its own strength.

Table 1 Examples of implementation of natural rubber bearings for seismic isolation

	Vert load (kN)	Horz natu- ral freq (Hz)	Vert natu- ral freq (Hz)	Permi- ssible horz shear disp(mm)	Breaking shear deflexion (500% shear strain)(mm)	Dimensions					
						Dia. of bearing (mm)	Rubber thickness x no of layers (mm)	Total dia. (mm)	Total height (mm)	Bearing comp. (MPa)	No. of R.B. used
O. Co. Lab. Bld.	1960	0.33	13.0	375	1342	765	4.4 x 61	985	466	4.753	14
K. Co. Acoustic Lab. Bld.	980	0.5	5.0	200	1140	780	38.0 x 6	1140	308	2.254	10
	1617	0.5	5.0	200	1200	1000	48.0 x 5	1340	320	2.254	8
T. Co. Dormitory Bld.	1470	0.5	19.0	300	690	686	6.0 x 23	940	242	4.1944	8
	1960	0.5	19.0	300	609	766	5.8 x 21	1080	226	4.6256	6
Elizabeth Saunders' Home Bld.	735	0.46	19.0	170	500	445	4.0 x 25	680	220	4.949	15
Office Bld. (const. by O. Co.)	1470	0.33	12.0	375	1298	666	5.9 x 44	860	451	4.6746	8
	2450	0.33	11.0	375	1350	756	6.0 x 45	985	470	5.9388	12
M. Material Lab. Bld. (Const. by O. Co.)	637	0.4	16.6	300	816	436	3.2 x 51	610	276	4.6648	32
Bridgestone Toranomon Bld. (Const. by S. Co.)	4900	0.33	13.0	300	972	896	5.4 x 36	1150	327	8.2908	5
	5880	0.33	13.0	300	930	976	6.2 x 30	1290	314	8.33	4
	7840	0.33	13.0	300	900	1046	6.0 x 30	1350	334	9.7706	3

Fig. 23 Example of implementation of rubber bearings

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