SEISMIC ISOLATION RUBBER BEARINGS FOR NUCLEAR FACILITIES

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This paper describes results of biaxial breaking tests by compression and shear and by tension and shear for seismic isolation rubber bearings with bolted-type connections. The bearings used in the tests were low-damping rubber bearings, high-damping rubber bearings, and lead-rubber bearings. Three modes of failure of the bolted-type bearings were observed in the tests. They are the breaking failure by tension and shear; the breaking failure by compression and shear; and the buckling failure by compression and shear. The first and the second modes of failures are almost independent of the types and the sizes of the bearings. The breaking conditions of those failure modes are described in the axial stress-shear strain plane. This expression is useful for the evaluation of safety margins of the bearings.

The paper outlines the basic design of the nuclear-grade bearings which were used for large-scale rubber bearing tests in a research project for seismic isolation of fast breeder reactor (FBR) plants. The paper also discusses the protection method against aging and the quality control which are important for implementation.

Introduction

In Japan, the use of seismic isolation rubber bearings in buildings has been progressing rapidly. These include low-damping (natural) rubber bearings,[1-4] high-damping rubber bearings,[5-7] and lead-rubber bearings developed in New Zealand.[8] About 20 base-isolated buildings have been constructed to date, and about 10 are now under construction. They are used as office, residential, and laboratory buildings. This demonstrates that the rubber bearings have become acceptable and are reliable enough for application to less critical buildings of normal use. For application to nuclear facilities, however, more intensive research is necessary so that rubber bearings with extraordinarily high reliability can be produced.

Since 1981, the author has engaged in the research and development of the rubber bearings in collaboration with a major rubber manufacturer who is one of the pioneer groups in research for rubber bearings in Japan.[9,10] The low-damping and high-damping rubber bearings developed by the author's group are bolted-type bearings that use bolts for connection to the isolated superstructure and the foundation. In the early stages of development, the reason for adopting the bolted-type bearings was because they were believed to have more consistent and more predictable dynamic behavior when subjected to three-dimensional seismic ground motions. In the later stage of development, the adoption was confirmed by the fact that for a given size of bearing and a given vertical load, the bolted-type bearings could accept considerably larger horizontal displacements than the doweled-type bearings.

Since 1987, a seven-year test and research project for application of seismic isolation to fast breeder reactor power plants, supported by the Ministry of International Trade and Industry (MITI), is being carried out by the Central Research Institute of Electric Power Industry (CRIEPI).[11] In this project, large-scale rubber bearings of three types (low-damping, high-damping, and lead type) are being tested.[12] All of the bearings use the bolted-type connection. (Note: For lead-rubber bearings the doweled-type connection has usually been used in Japan, New Zealand, and the United States.)

For the bolted-type of bearing, the strength of bond between the rubber sheets and the steel plates must be improved so the possible break position occurs only in the rubber layers. Such rubber bearings obey simple breaking conditions even under biaxial loads of compression and shear, and of tension and shear. This behavior has been shown by various breaking tests. The breaking conditions enable us to evaluate safety margins of the bearings designed for given specifications.

This paper summarizes the results of the breaking tests for three types of rubber bearings and depicts possible failure modes of the bolted-type bearings from the results. The paper also discusses the basic design of the rubber bearings for nuclear facilities, protection of the bearings against aging, and quality control of the bearings.

Breaking Tests of Low-Damping Rubber Bearings

The low-damping rubber bearing is a natural rubber bearing with a normal energy absorbing capacity, which provides the base-isolated buildings with a damping ratio of about 2%. The rubber bearing needs additional energy-absorbing devices to form the appropriate seismic isolation systems with effective damping ratios of 10 to 20%.

1. Rubber Bearing for Breaking Tests

The rubber bearing of a 980-kN rated load and its 0.4-scale model were used to investigate the breaking conditions of the low-damping rubber bearing.[3,4] The full-scale bearing comprising 27 natural rubber sheets of 6-mm thickness and 600-mm diam bonded to steel plates, was designed to provide the 100-ton rated mass with a horizontal natural frequency of 0.51 Hz and a vertical frequency of 21 Hz (Fig. 1). The design compressive stress for the rated load was 3.47 MPa. The characteristic values of physical properties of the rubber were as follows:

Hardness (IRHD) = 40, G_{100} = 0.58 MPa, e_B = 6.5,

where G_{100} expresses the shear modulus at a 100% shear strain and e_B is the breaking tensile strain.

2. Biaxial Breaking Test by Compression and Shear

Biaxial breaking tests by compression and shear were carried out for the 0.4-scale models. The tests were performed using a test apparatus that can exert vertical loads and horizontal displacements on a pair of bearings in which one bearing is placed on top of the other, while keeping the top surface of the upper and the bottom surface of the lower bearing parallel to a link mechanism.

Figure 2 shows the test results for six pairs of bearings under compressive stresses up to two times the design stress. The breaking shear strains are almost independent of the compressive stresses and are about 500% corresponding to a shear deflection of 0.8 m in full size, which is larger than the diameter of the bearing. This result could be explained by the fact that, as shown in Fig. 3, contact of the side of the bearing to the top and bottom flanges effectively increases the overlapping area of the top and bottom surfaces to support the vertical load. The breaking shear stresses are 1.6 or 1.7 times the design compressive stress, which means that a horizontal acceleration of 1.6 or 1.7 g is needed to break the bearing by an inertia force of the rated mass.

3. *Biaxial Breaking Test by Tension and Shear*

Biaxial breaking tests by tension and shear were carried out for nine pairs of the 0.4-scale models, using test apparatus in which two bearings keeping a shear deflection given by a horizontal jack between them were pulled up by a vertical jack. Figure 4 shows a part of the results where (a) is the results under no shear strain, (b) is the result under a 185% shear strain, and (c) is the result under a 309% shear strain, and where the values in parentheses represent full size. The test results showed that though the breaking tensile forces decreased with increasing shear deflection, the breaking forces (0.80 to 0.94 times the rated load) are still large even under a shear deflection of 0.3 m in full size.

Breaking tests by simple tension without shear were also carried out for the full-scale bearings, showing that the breaking tensile forces are larger than the rated load (1.2 to 1.9 times).

4. *Breaking Conditions*

The breaking conditions under the biaxial loads are expressed in a plane with a vertical axis representing the axial stresses of the bearing (the positive part of the axis was for the tensile stresses and the negative part for the compressive stresses) and a horizontal axis representing the breaking shear strains. From all of the test results, the conditions shown in Fig. 5 were obtained for the 980-kN bearing, where the dotted line connecting the average values of the test results shows the boundary between areas with and without occurrence of the breaking in the plane.

Breaking Tests of High-Damping Rubber Bearings

The high-damping rubber bearings are those using rubber materials with energy-absorbing capacities enhanced by mixing filler. The high-damping bearings can provide the base-isolated buildings with proper damping for seismic isolation. This type of bearing was first used in the United States.[13]

1. *Rubber Bearings for Breaking Tests*

The bearings used for breaking tests were 0.5-scale models of the bearing of a 784-kN rated load shown in Fig. 6 (Ref. 6). The full-scale bearing was designed to provide the 80-ton rated mass with a horizontal effective natural frequency of about 0.5 Hz under an amplitude of ±0.15 m, a vertical natural frequency of 20 Hz, and an effective damping ratio of about 15% under the amplitude. The design compressive stress was 4.93 MPa. The characteristic values of the rubber are as follows:

Hardness (IRHD) = 60, G_{100} = 0.85 MPa, e_B = 7.2.

Figure 7 shows hysteretic restoring force characteristics of the full-scale bearing obtained by cyclic deformation tests.[5]

2. Biaxial Breaking Test by Compression and Shear

The tests were carried out for three pairs of the 0.5-scale models using the same test rig as for the low-damping bearing tests mentioned above. The test results given in Fig. 8 show that the breaking shear strain slightly decreases with increased compressive stress, while the breaking shear stress considerably decreases with increased compressive stress. Under the design compressive stress, the breaking strain corresponded to a 0.66-m shear deflection in full size, which is larger than the diameter, and the breaking shear stress is 1.1 times the design compressive stress. These values concerning the breaking have enough safety margins for implementation to normal buildings, although the margins decrease compared with the low-damping bearing because of the design compressive stress increase.

However, for pairs B and D, the shear stress-strain relations have local peaks and negative slopes in the ranges of shear strain smaller than the breaking strains, although distortions in those ranges are conspicuous. These distortions were caused by the fact that ram speed of the hydraulic actuator, which exerts the vertical loads to bearings, could not follow the speeds of height reduction of the pairs of the bearings. Consequently, frequent interruption of forcing and horizontal displacements was necessary to adjust the vertical loads. These results and facts suggest that buckling may have occurred in the bearings. In such a case, the limit of acceptable deflection of the bearing should be determined by the buckling, because the bearing will not be able to restore the superstructure to its original position at deflections beyond this limit. For the bearing tested, the limit shear strain under the design compressive stress was about 350%, corresponding to about a 0.5-m deflection in full size which is large enough for implementation to normal buildings.

3. *Biaxial Breaking Tests by Tension and Shear*

The tests were performed by using the same test apparatus as that used for the low-damping bearing. Figure 9 shows the results obtained for three pairs of the 0.5-scale models with shear strains of 0, 174, and 290%. The breaking tensile forces were 0.83, 0.64, and 0.59 times the rated load under shear deflections of 0, 0.24, and 0.40 m in full size, respectively. The increased design compressive stress decreases safety margins in the breaking tensile forces compared with the case of the low-damping bearing, although relations between the breaking tensile stresses and the shear strains are similar to those of the low-damping bearing.

4. *Breaking Conditions*

Breaking conditions for the high-damping bearing are described in the axial stress-shear strain plane as used for the low-damping bearing. Figure 10 shows the conditions obtained from the test results together with those for the low-damping bearing. The conditions for both types of bearing agree well with each other. In the case of the high-damping bearing, however, the acceptable shear strains under compressive stresses larger than the design stress must be reduced because of the buckling, which is not included in Fig. 10.

4. Breaking Tests of Lead-Rubber Bearings

The lead-rubber bearing is the natural rubber bearing with a lead plug inserted at its center hole, which works as an internal hysteretic damper for seismic isolation.

1. *Rubber Bearings for Breaking Tests*

The bearings used for breaking tests and other tests were 0.1- and 0.27-scale models of a 4900-kN rated load bearing shown in Fig. 11 (Ref. 14). The full-scale bearing and its scale models were designed for preliminary study of the bearings for nuclear facilities. The full-scale bearing without the lead plug had stiffnesses to provide the 500-ton rated mass with a horizontal natural frequency of 0.5 Hz and a vertical frequency of 20 Hz. The lead plug was designed to provide the restoring force-displacement relation of the bearing with a hysteresis loop having a total width of 420-kN along the force axis. The design compressive stress was 2.44 MPa. The rubber material of the lead-rubber bearing was the same as that of the low-damping bearing.

Figure 12 shows restoring force characteristics of the bearing together with those of the bearing without the lead plug for comparison, which were obtained by cyclic deformation tests for the 0.27-scale model.

2. Durability Against Repeated Deformations

Durability against repeated shear deformations is important to seismic isolation rubber bearings, particularly the lead-rubber bearing, because it utilizes elastoplastic deformation of the lead plug, of which the integrity is unable to be inspected from outside the bearing. To investigate the durability, 20 time-repetition tests of four-cycle deformation (the total cycle of 80) with a ten-minute interval between the times, were carried out for the 0.1-scale models under the design compressive stress. The tests were completed using a test rig of a different type from that used for the low- and the high-damping bearings.

Figure 13 compares the shear stress-strain relation obtained by the 1st and the 20th four-cycle deformation tests under a shear strain amplitude of ±227% corresponding to a 0.5-m shear deflection in full size, where no significant change is observed between the relations. This means that both the rubber and the lead plug could keep their integrity through the repetition test. Figure 14 shows the relations by the 1st and the 20th tests under a strain amplitude of ±445% corresponding to a 0.98-m displacement in full size which were carried out for another 0.1-scale model. The relation by the first test was unsteady because of likely formation of vacuoles in the rubber due to cavitation; nevertheless, the relation by the 20th tests maintained the specified hysteresis loop. This repetition test verified that the rubber and the lead plug had the fatigue resistance even against repeated deformations of such a large displacement.

3. Breaking Test by Compression and Shear

The test results are shown in Fig. 15, where the results denoted by A and B are for the 0.1-scale models without the lead plug, and those denoted by E and F are for the models under two times the design compressive stress. The results of C to F mean that the breaking shear deflections in full size were 1.1 to 1.2 m under vertical loads up to two times the rated load, and that the breaking shear forces were 4.0 to 4.6 times the rated load. These values imply the large safety margins which resulted from the low design compressive stress.

Comparing the results of A and B with those of C and D, it is obvious that the lead plug scarcely affects the breaking by compression and shear. Furthermore, it can also be assumed that the lead plug does not affect the breaking by tension and shear. Therefore, it can be concluded that the lead-rubber bearings obey the breaking conditions similar to those of the low-damping bearings and of the high-damping bearings as well.

Failure Modes of Rubber Bearings using Bolted-Type Connections

The results of the breaking tests mentioned above suggest three modes of failure for the bolted-type bearings: (1) breaking by tension and shear; (2) breaking by compression and shear; and (3) buckling by compression and shear.

Figure 16 illustrates the occurrence conditions of the three modes of failure described in the axial stress-shear strain plane. The boundaries AB, BC, and DE are for the breaking by tension and shear, the breaking by compression and shear, and the buckling by compression and shear, respectively. Point D corresponds to the minimum compressive stress with the possibility of inducing the buckling, which makes a boundary for pattern change of the shear stress-strain relation, as shown in Fig. 16.

According to the test results, the boundaries AB and BC are almost independent of the types of the bearings including the low- and high-damping types, and the lead type, and are also almost independent of the sizes of the bearings. They are determined mainly by the strength of the rubber materials, which strongly depends on the vulcanization conditions. For boundary DE, however, useful knowledge and analytical methods to predict it have not been obtained. Future studies are required.

Basic Design of Rubber Bearings for Nuclear Facilities

In the CRIEPI test and research project for seismic isolation of FBR plants, in which the author is involved, three types of bearings having a 4900-kN rated load have been designed for research purposes. In this paper, the design of the low-damping bearing is outlined to show the basic design concept applied to the bearings.

The low-damping bearing was designed according to the basic design specifications as follows:

1. horizontal stiffness to provide the 500-ton rated mass with a natural frequency of 0.5 Hz, which was adopted for the seismic isolation system to perform sufficient reduction in seismic response accelerations for implementation and, at the same time, not to amplify the sloshing response of the coolant in the reactor vessel;
2. vertical stiffness to provide the rated mass with a natural frequency of 20 Hz adopted to suppress the vertical response amplification to a minimum;
3. allowable horizontal deflection with the linear horizontal stiffness of 0.5 m, which was adopted for the system to maintain the isolation performance against the design earthquakes with enhanced low-frequency components. (Note, a tentative design response spectrum is being proposed for critical facilities,[15] which requires a large safety margin.)
4. breaking horizontal deflection of about 1 m, which is provided by a shear strain of about 450%.

The third specification mentioned above means that the breaking horizontal deflection inevitably becomes larger than 1 m, because the linear stiffness is maintained for shear strains up to about 250%, and the breaking occurs at a shear strain of about 500% under a low design compressive stress (see Figs. 2 and 15).

In this project, to carry out the breaking tests for scale models which are as large as possible, another specification was added as follows:

Figures 17 and 18 show the low-damping rubber bearing of full scale. The design compressive stress is 2.48 MPa, which is low enough to provide the bearing with large safety margins against breaking and buckling. The tests were carried out for the full-scale bearing, the 0.633-scale models comprising rubber sheets of 1.012-m diam, and the 0.316-scale models comprising rubber sheets of 0.506-m diam, using huge test apparatus equipped with a lateral load actuator of a 5880-kN load capacity and a ±0.6-m (or 1.2-m) stroke, and an axial load actuator of a 5880-kN load capacity and a ±0.35-m (or 0.7-m) stroke. Through the tests, including the breaking tests by compression and shear for both of the scale models, it was confirmed that the bearing met the specifications well.[12]

Protection Against Aging and Quality Control

Durability of the rubber bearings against aging is very important for implementation. The rubber materials based on natural rubber are used not only for the low-damping and the lead types, but also for the high-damping type, because natural rubber has desirable performance against creep. However, its durability against aging is not always satisfactory when exposed to ozone, oxygen, and ultraviolet rays. Therefore, the rubber manufacturer, collaborating with the author, developed a special structure of the bearing in which, as shown in Fig. 19, the inner rubber is protected by the surface rubber of a synthetic rubber material with a high durability against aging. The surface rubber is vulcanized together with the inner rubber in the mold. Figures 20 and 21 show the difference between the durabilities of the inner rubber and the surface rubber.

Furthermore, quality control of the bearings is important for implementation. For the bearings applied to base-isolated buildings of normal use, strict checks are already done at various stages of the manufacturing process, as shown in Fig. 22. For the bearings applied to nuclear facilities, more strict and detailed inspections are necessary to guarantee the performance required by the design specifications. In the project for FBR plants, several new inspections are being implemented for quality assurance, especially for the assurance of the rubber and the bond strength. Even for the bearings used in the tests, inspections under severe acceptance conditions are carried out for their horizontal stiffness under deflections up to those allowable (0.5 m in full size) and their vertical stiffnesses. These experiences will contribute to the establishment of quality control methods suitable for nuclear facility bearings.

Conclusions

Performance and reliability of the rubber bearings in their present state has convinced many engineers and researchers engaged in the nuclear industry of the application of seismic isolation to nuclear facilities. Their application will become more practical as intensive research including static breaking tests of large-scale bearings and degraded bearings, and excitation tests of large-scale models of base-isolated reactor buildings, etc., confirms the performance and the reliability of the bearings and establishes the design and quality control methods. Such intensive research has already begun.

For application to nuclear facilities, however, it is necessary that seismic isolation is accepted not only by the specialists, but also by the public. Fortunately, the number of base-isolated buildings increases by the year in Japan, and the situation is becoming real. Therefore, conditions for the application of seismic isolation are being satisfied.

References

1. T. Fujita, S. Fujita, S. Suzuki, and T. Yoshizawa, "Experimental Study of Laminated Rubber Bearings for Earthquake Isolation of Buildings (1st Report, Static Tests for Rubber Bearings of 490 kN Rated Load)," Trans. of Japan Soc. Mech. Engrg. 53, Ser. C, 71-76 (1987) (in Japanese).

2. T. Fujita, S. Fujita, S. Suzuki, and T. Yoshizawa, "Experimental Study of Laminated Rubber Bearings for Earthquake Isolation of Buildings (2nd Report, Static Tests for Rubber Bearings of 980 kN Rated Load)," ibid., 77-81 (in Japanese).

3. T. Fujita, S. Fujita, S. Suzuki, and T. Yoshizawa, "Experimental Study of Laminated Rubber Bearings for Earthquake Isolation of Buildings (3rd Report, Breaking Tests for Rubber Bearings of 980 kN Rated Load)," Trans. Japan Soc. Mech. Engrg. 54, Ser. C, 2618-2623 (1988) (in Japanese).

4. T. Fujita, S. Fujita, S. Tazaki, T. Yoshizawa, and S. Suzuki, "Research, Development, and Implementation of Rubber Bearings for Seismic Isolation," ASME PVP Conf., JSME Co-Sponsorship, Honolulu, HI (July 23-27, 1989).

5. T. Fujita, S. Suzuki, and S. Fujita, "High Damping Rubber Bearings for Seismic Isolation of Buildings (1st Report, Hysteretic Restoring Force Characteristics and Analytical Models)," Trans. Japan Soc. Mech. Engrg., 56, Ser. C, 658-666 (1990) (in Japanese).

6. S. Suzuki, T. Fujita, and M. Shimazaki, "High Damping Rubber Bearings for Seismic Isolation of Buildings (2nd Report, Breaking Tests)," ibid., 667-672 (in Japanese).

7. T. Fujita, S, Suzuki, and S. Fujita, "Hysteretic Restoring Force Characteristics of High Damping Rubber Bearings for Seismic Isolation," ASME PVP Conf., JSME Co-Sponsorship, Honolulu, HI (July 23-27, 1989).

8. W.H. Robinson, "Lead-Rubber Hysteretic Bearings Suitable for Protecting Structures During Earthquakes," Int. J. Earthq. Engrg. Struct. Dyn. 10, 593-604 (1982).

9. T. Fujita, S. Fujita, and T. Yoshizawa, "An Aseismic Base Isolation System Using Laminated Rubber Bearings for Heavy Mechanical Equipment (1st Report, Fundamental Study on Isolation Device - Part 1)," SEISAN-KENKYU (monthly report of the Institute of Industrial Science, University of Tokyo), 34, 64-67 (1982) (in Japanese).

10. T. Fujita, "Earthquake Isolation Technology for Industrial Facilities - Research, Development and Applications in Japan," Bull New Zealand Natl. Soc. Earthq. Engrg. 18, 224-249 (1985).

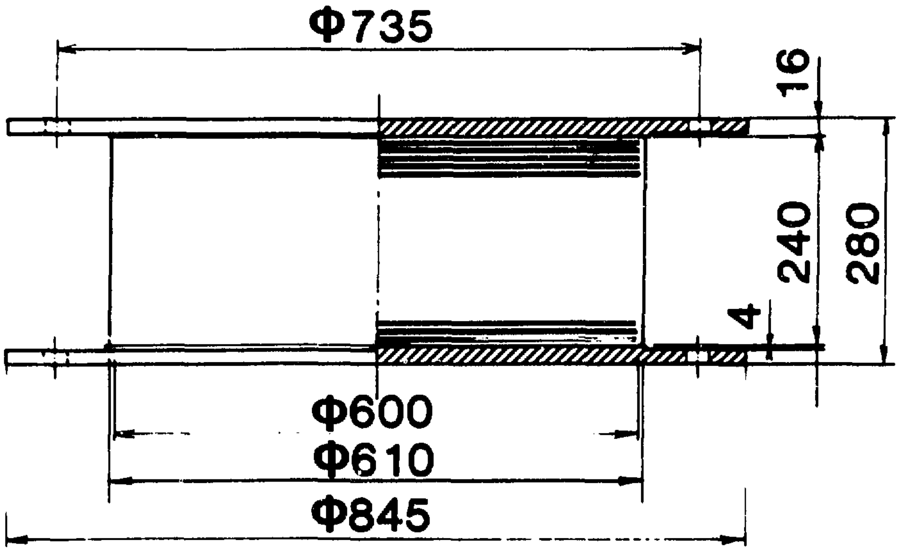
11. Y. Sawada. H. Shiojiri, C. Kurihara, Y. Maeno, S. Aoyagi, H. Shimizu, T. Goto, H. Shibata, T. Fujita, Y. Kitagawa, M. Shigeta, and K. Takabayashi, "Seismic Isolation Test Program," 10th SMiRT, Div. K, Anaheim, CA (Aug. 14-18, 1989).

12. T. Mazuda, H. Shiojiri, Y. Oka, T. Fujita, and M. Seki, "Tests on Large-Scale Seismic Isolation Elements - Preliminary Report," 10th SMiRT, Div. K, Anaheim, CA (Aug. 14-18, 1989).

13. C.J. Derham, J.M. Kelly, and A.G. Thomas, "Nonlinear Natural Rubber Bearings for Seismic Isolation," Nucl. Engrg. Design 84, 417-428 (1985).

14. T. Fujita, M. Ikenaga, and I. Shimoda, "Experimental Study of Hysteretic Restoring Force Characteristics and Break Conditions of Lead-Rubber Bearings (The Case of Bolt-Type Connection)," Trans. Japan Soc. Mech. Engrg., to appear (in Japanese).

15. K. Ishida, Y. Sawada, K. Irikura, K. Seo, and M. Takemura, "Tentative Design Response Spectrum for Seismically Isolated FBR," 10th SMiRT, Div. K, Anaheim, CA (Aug. 14-18, 1989).



Rubber sheet : $6\text{mm}^{T} \times 27 = 162\text{mm}$

Steel plate : $3\text{mm}^{T} \times 26 = 78\text{mm}$

Fig. 1. Low-Damping Rubber Bearing of 980-kN Rated Load

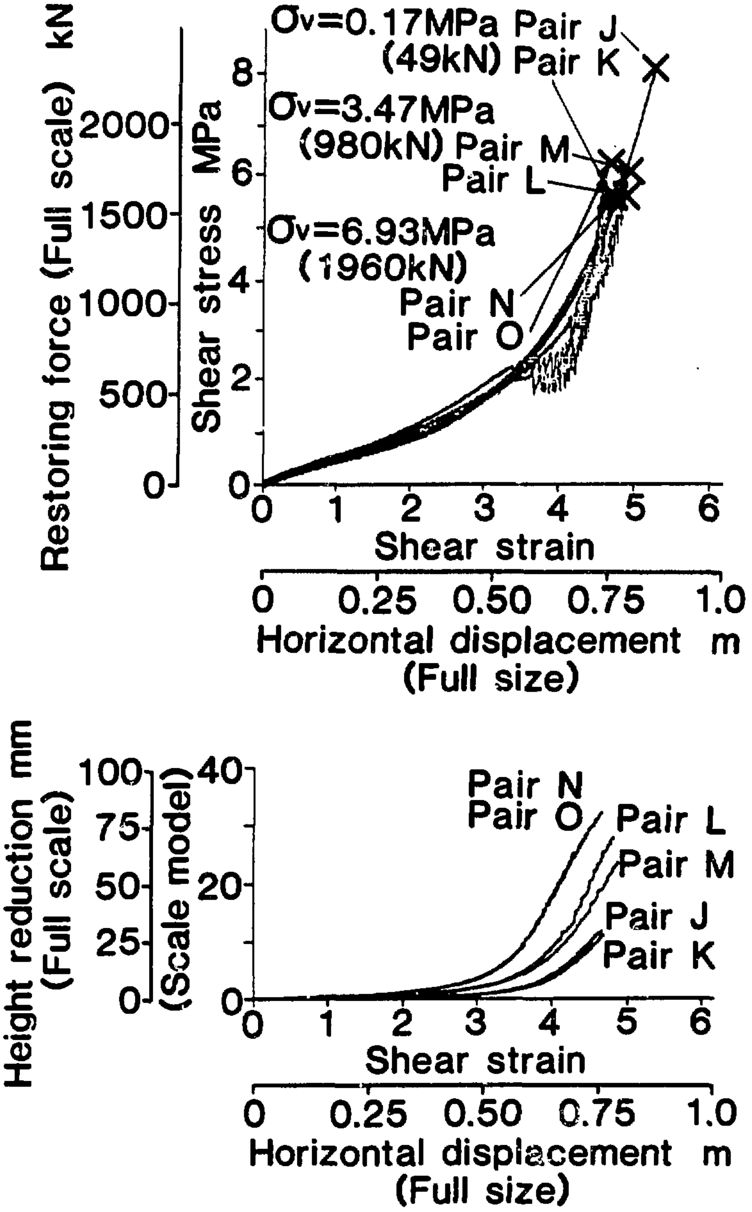


Fig. 2. Results of Breaking Tests by Compression and Shear for the Low-Damping Bearing

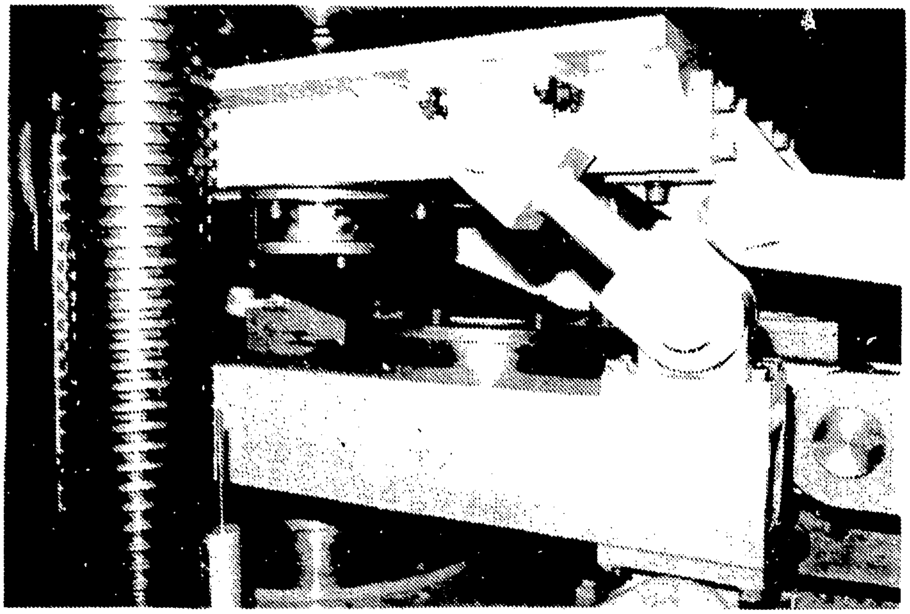


Fig. 3. Low-Damping Bearings in Break Test by Compression and Shear

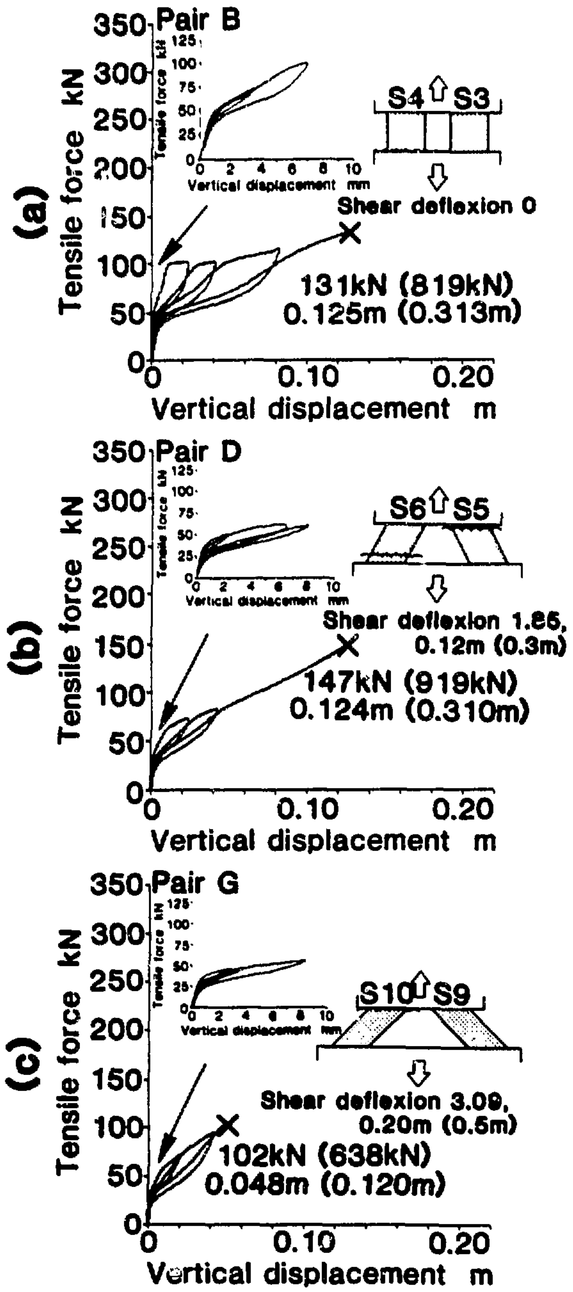


Fig. 4. Results of Breaking Tests by Tension and Shear for the Low-Damping Bearing

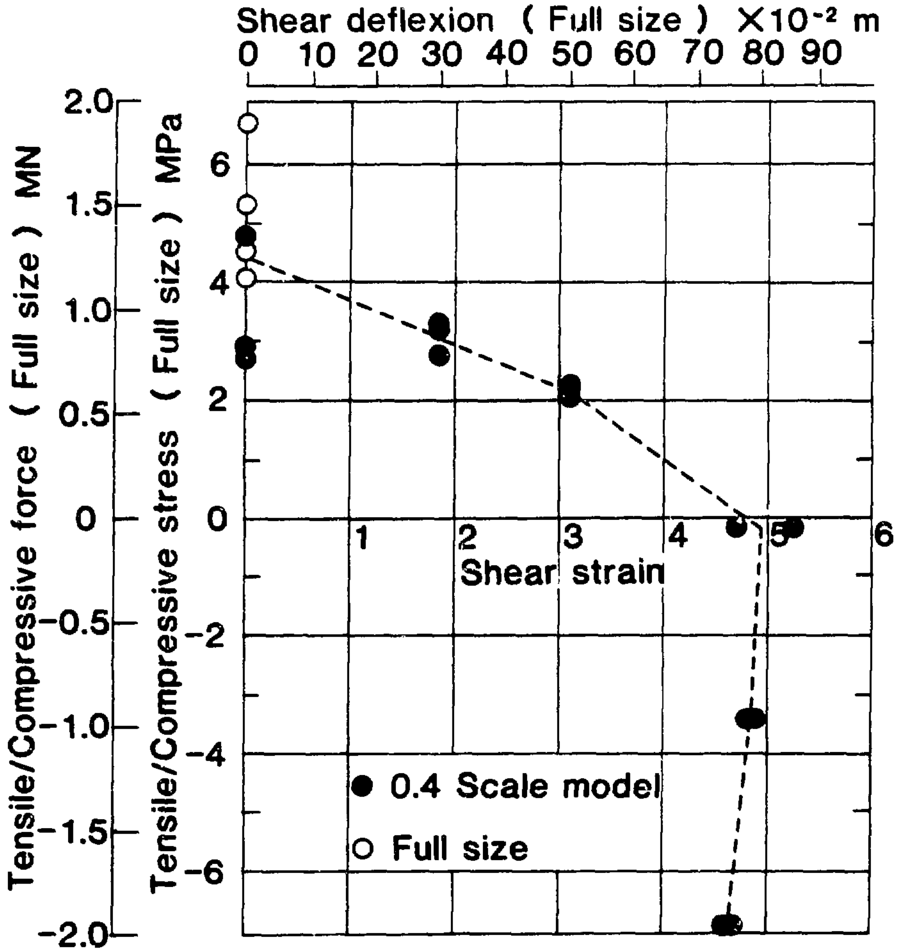


Fig. 5. Breaking Conditions for the Low-Damping Bearing

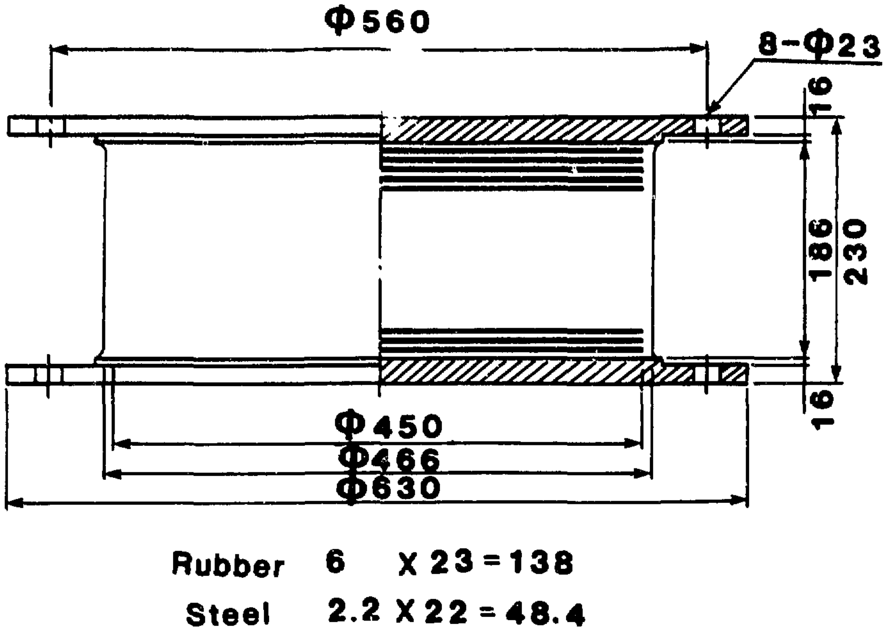


Fig. 6. High-Damping Rubber Bearing of 784-kN Rated Load

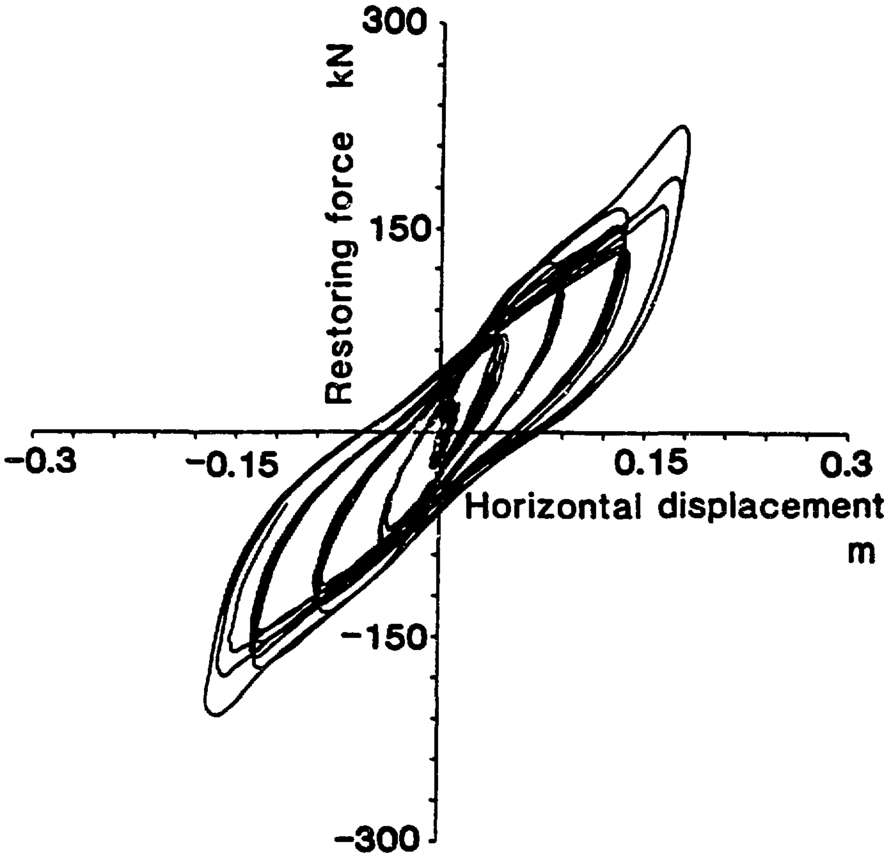


Fig. 7. Restoring Force versus Horizontal Displacement for the High-Damping Bearing

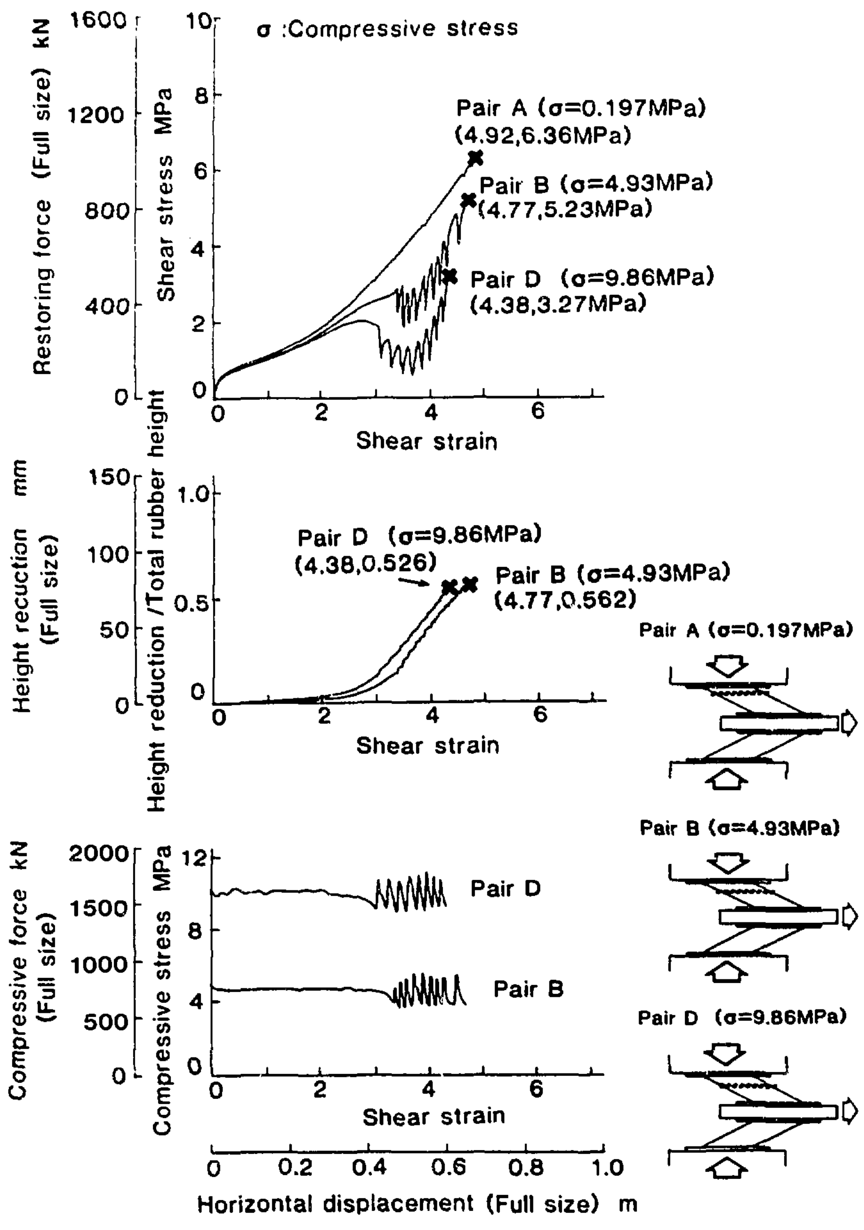


Fig. 8. Results of Breaking Tests by Compression and Shear for the High-Damping Bearing

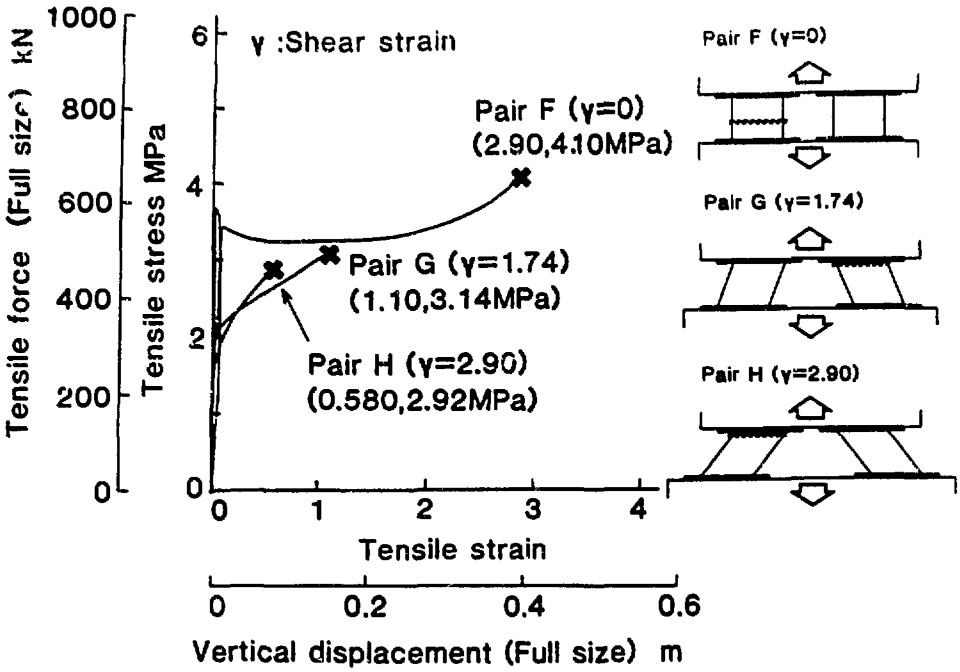


Fig. 9. Results of Breaking Tests by Tension and Shear for the High-Damping Bearing

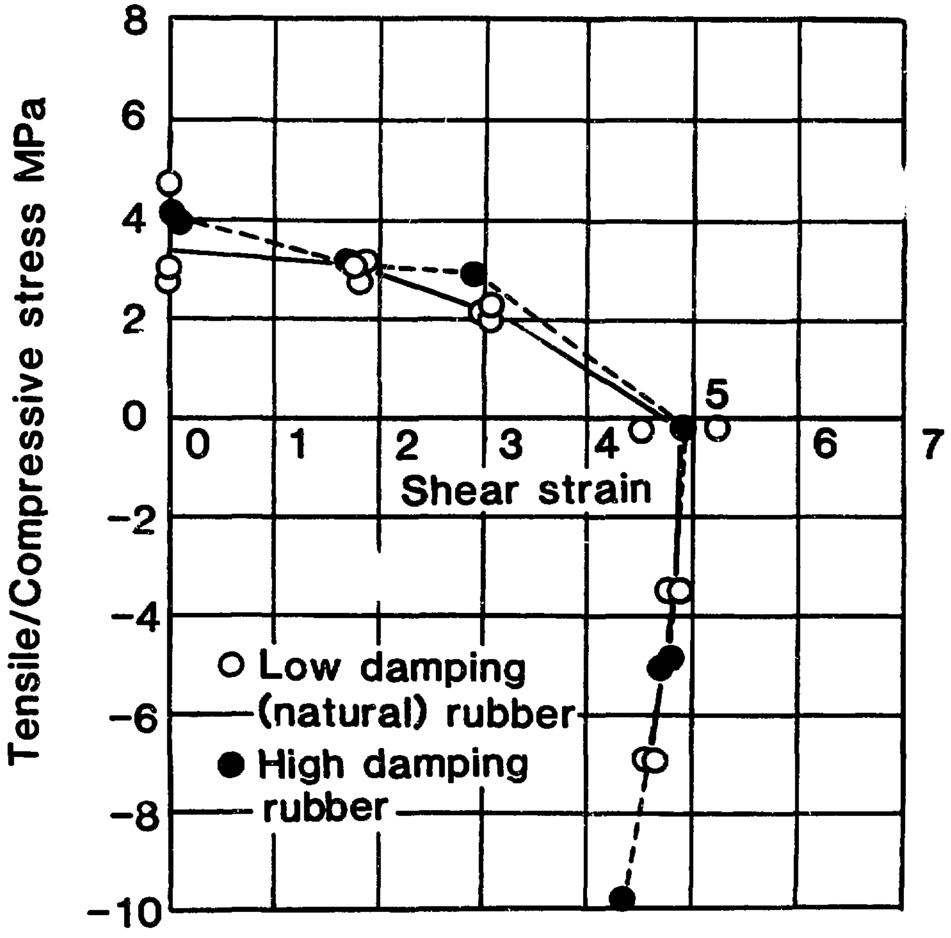


Fig. 10. Breaking Conditions for the High- and Low-Damping Bearings

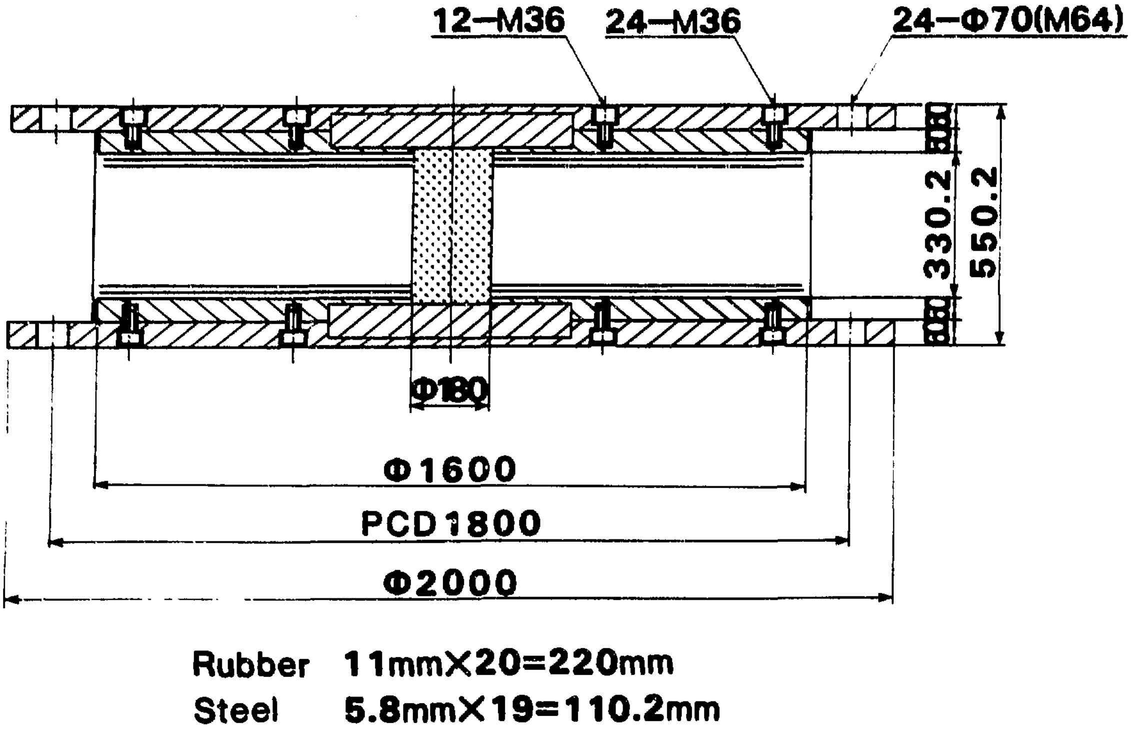


Fig. 11. Lead-Rubber Bearing of 4900-kN Rated Load

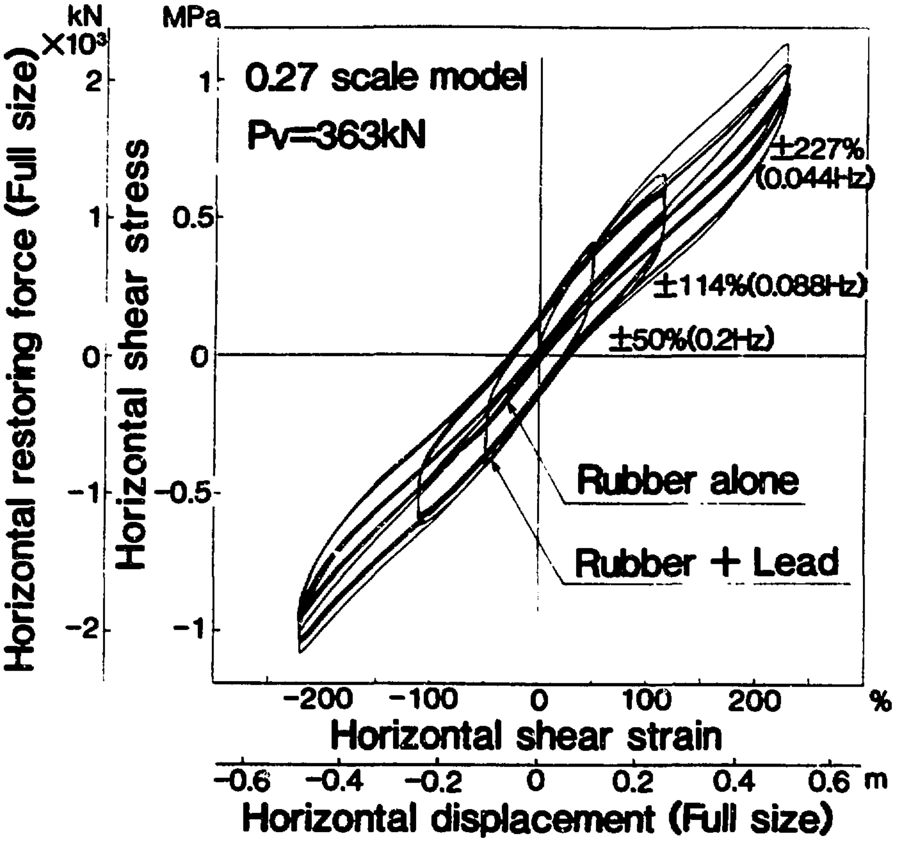


Fig. 12. Horizontal Shear Stress versus Shear Strain for the Lead-Rubber Bearing

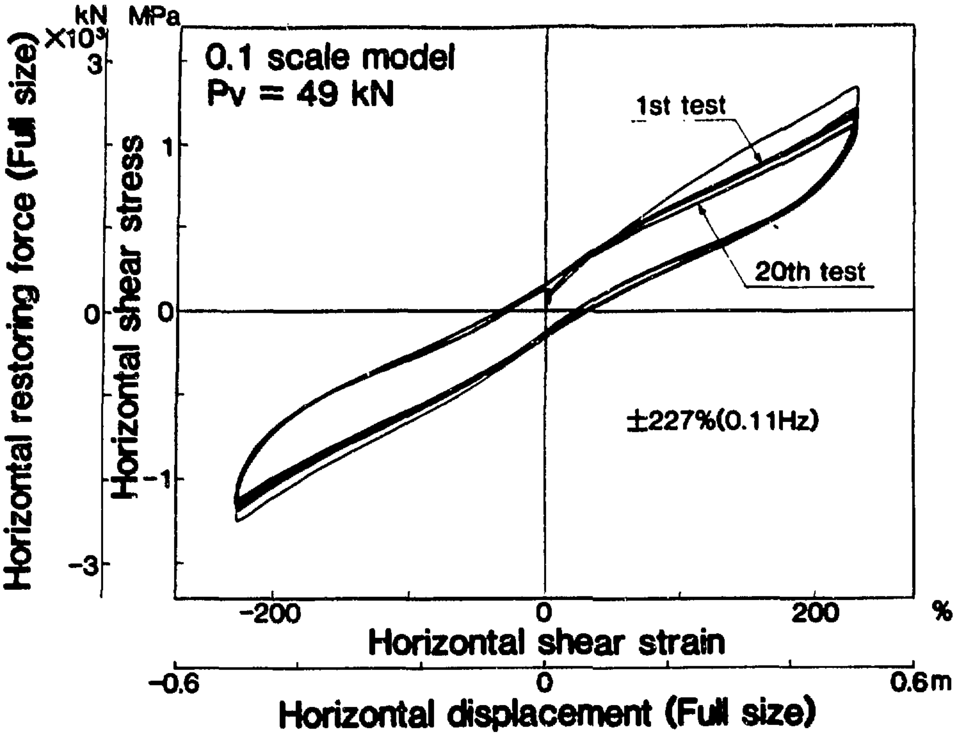


Fig. 13. Results of Repetition Test Under ±227% Shear Strain Amplitude for the Lead-Rubber Bearing

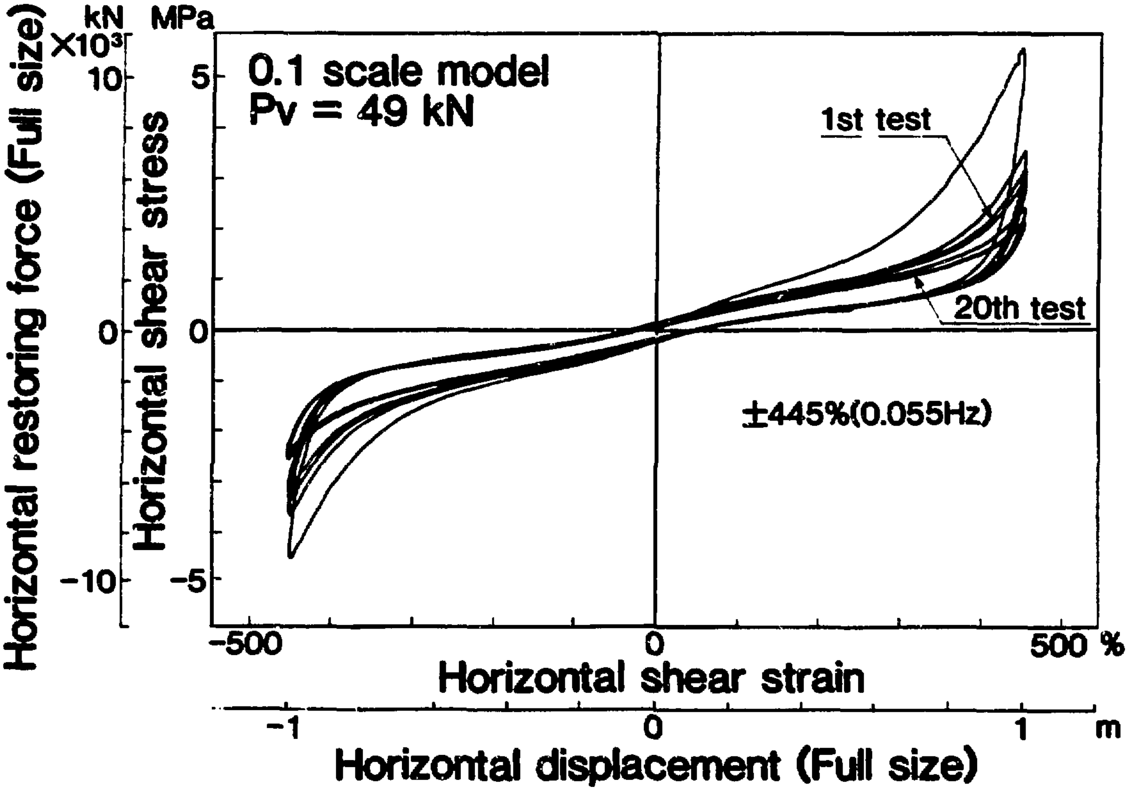
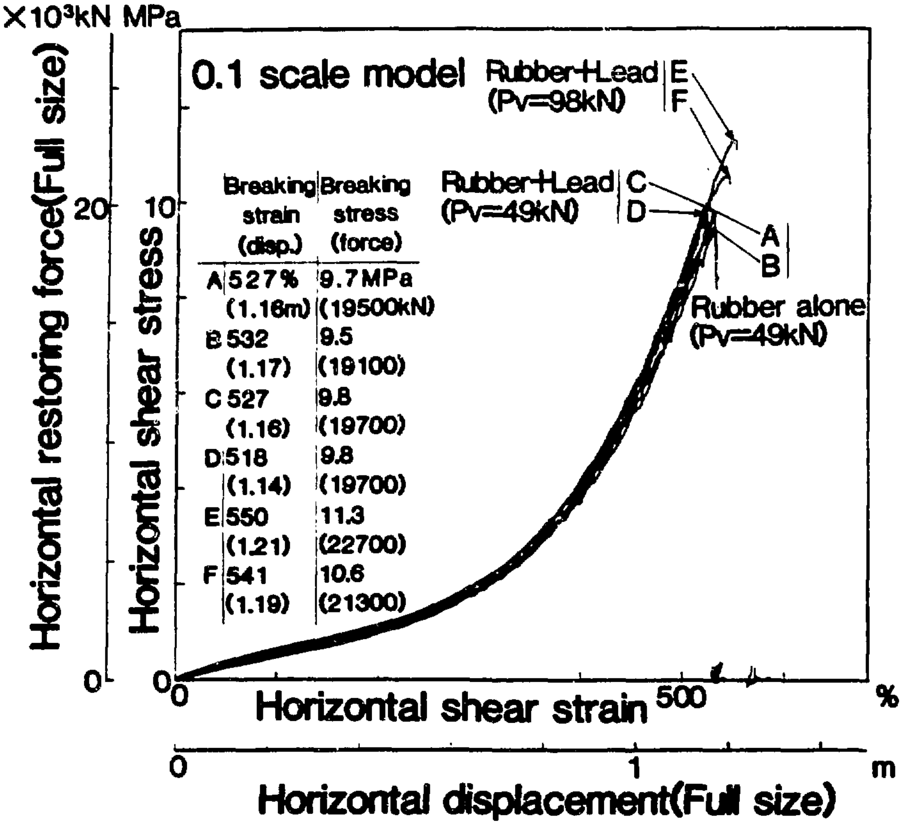


Fig. 14. Results of Repetition Test Under ±445% Shear Strain Amplitude for the Lead-Rubber Bearing



	Breaking strain (disp.)	Breaking stress (force)
A	527% (1.16m)	9.7MPa (19500kN)
B	532 (1.17)	9.5 (19100)
C	527 (1.16)	9.8 (19700)
D	518 (1.14)	9.8 (19700)
E	550 (1.21)	11.3 (22700)
F	541 (1.19)	10.6 (21300)

Fig. 15. Results of Breaking Tests by Compression and Shear for the Lead-Rubber Bearing

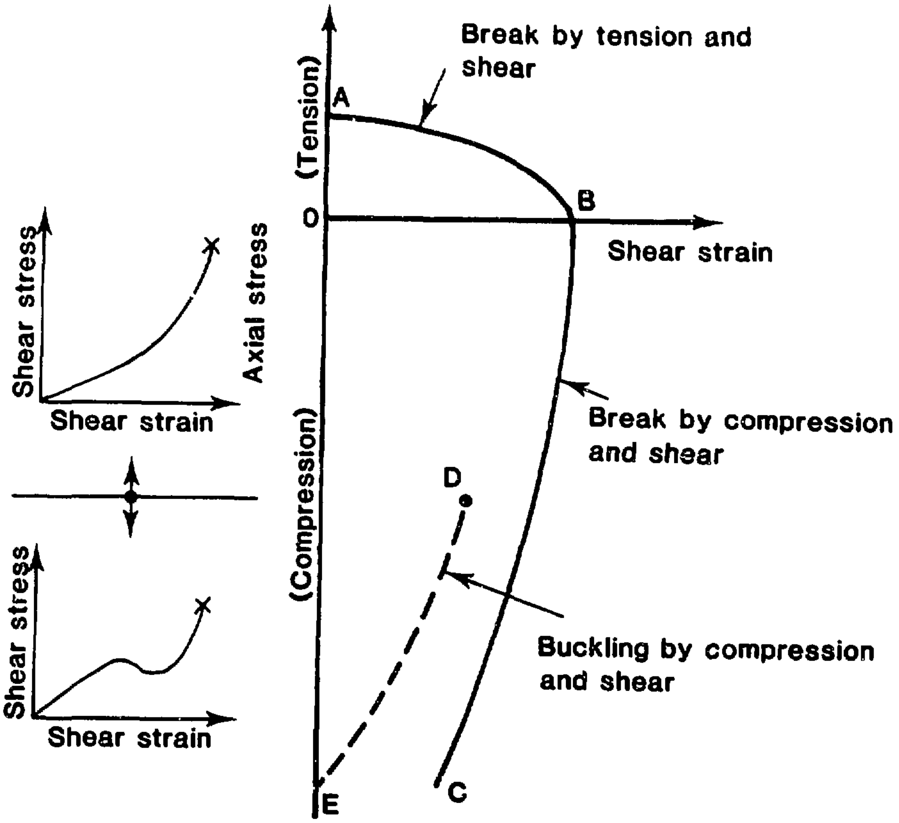
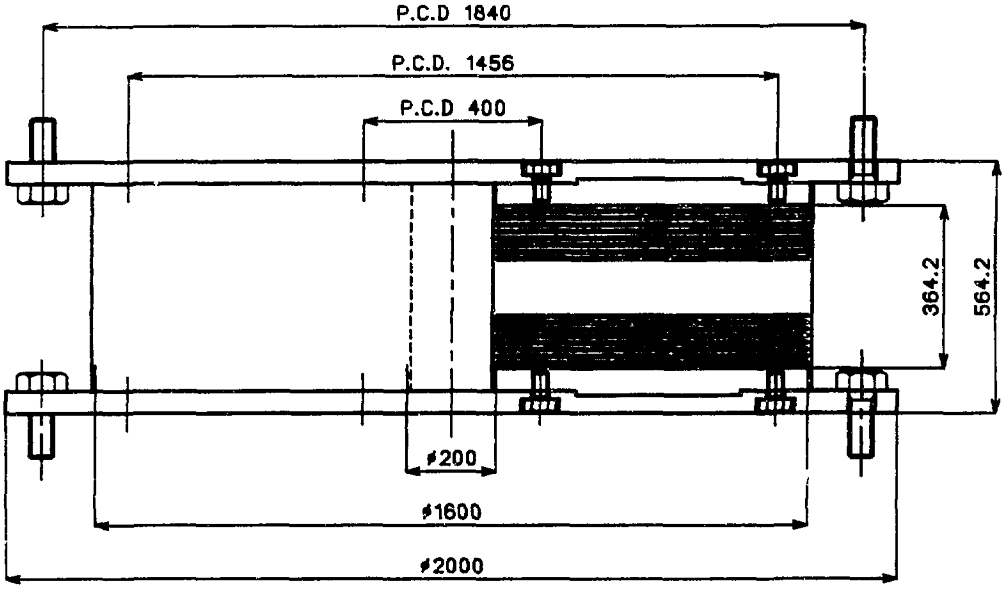


Fig. 16. Occurrence Conditions of Three Modes of Failure for Bolted-Type Bearing



RUBBER 9.0mmX25Layers

STEEL 5.8mmX24Layers

Fig. 17. Low-Damping Bearing of 4900-kN Rated Load for Nuclear Facilities

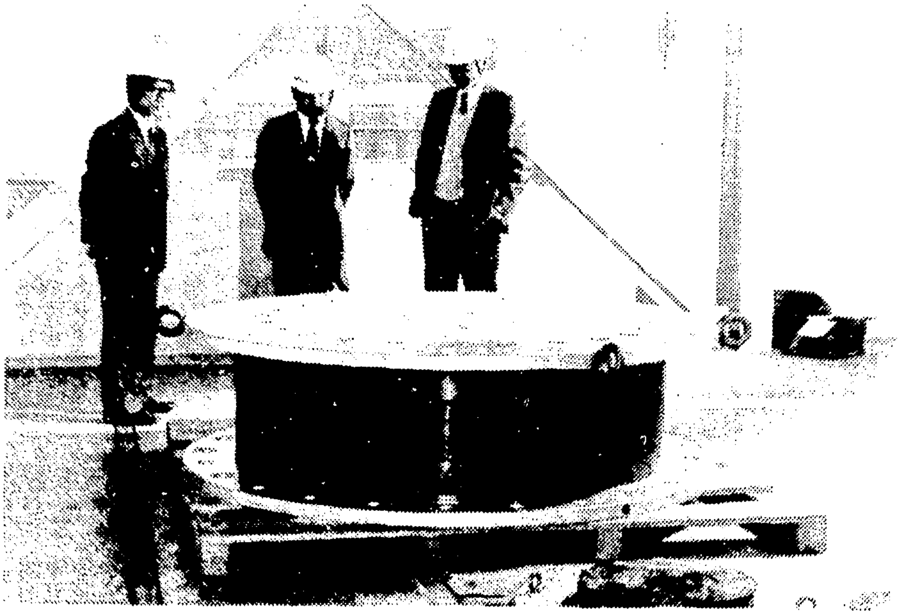


Fig. 18. Full-Scale Bearing for Tests

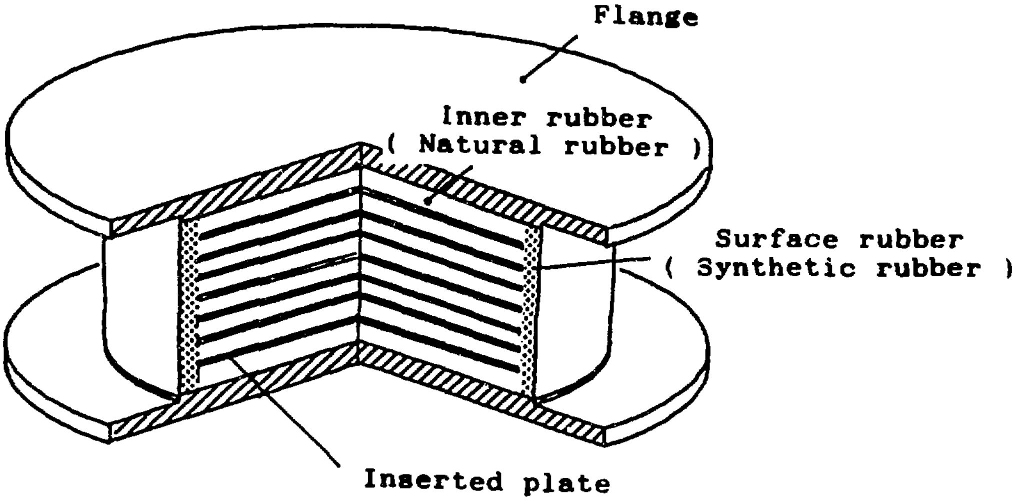


Fig. 19. Rubber Bearing Structure for Protection Against Aging

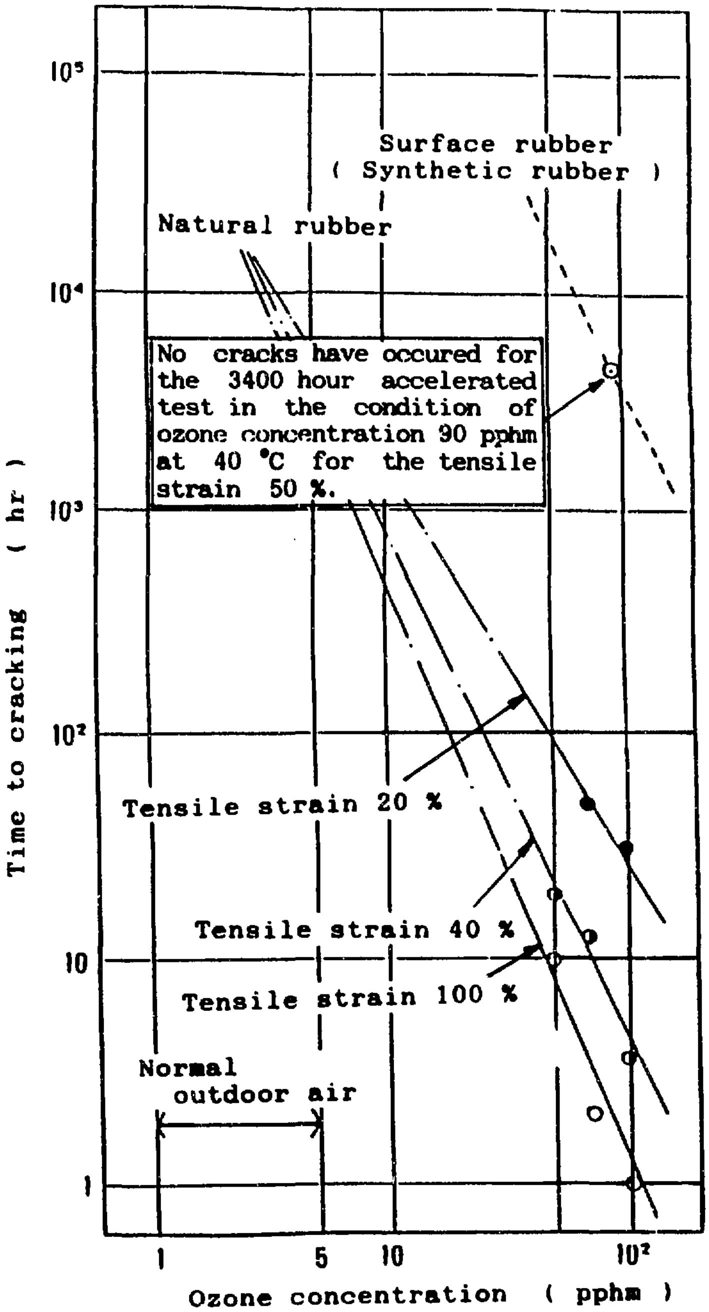


Fig. 20. Degradation of Surface and Inner Rubber in Ozone Atmosphere

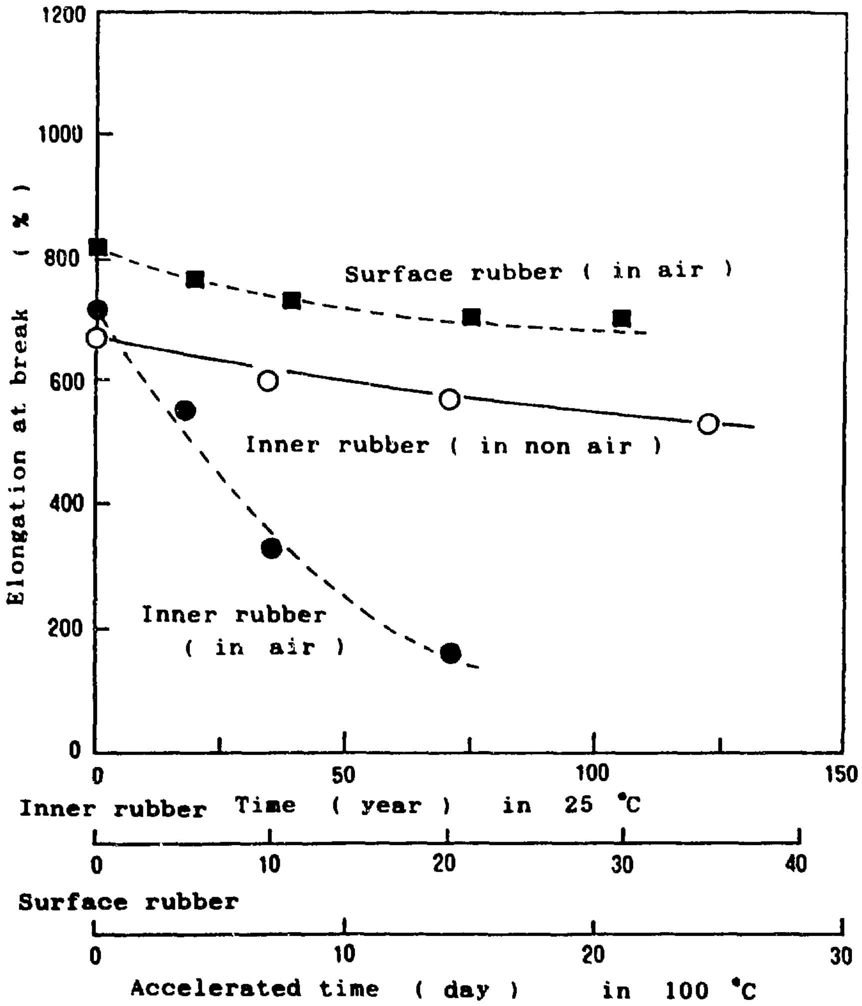


Fig. 21. Aging of Surface and Inner Rubber

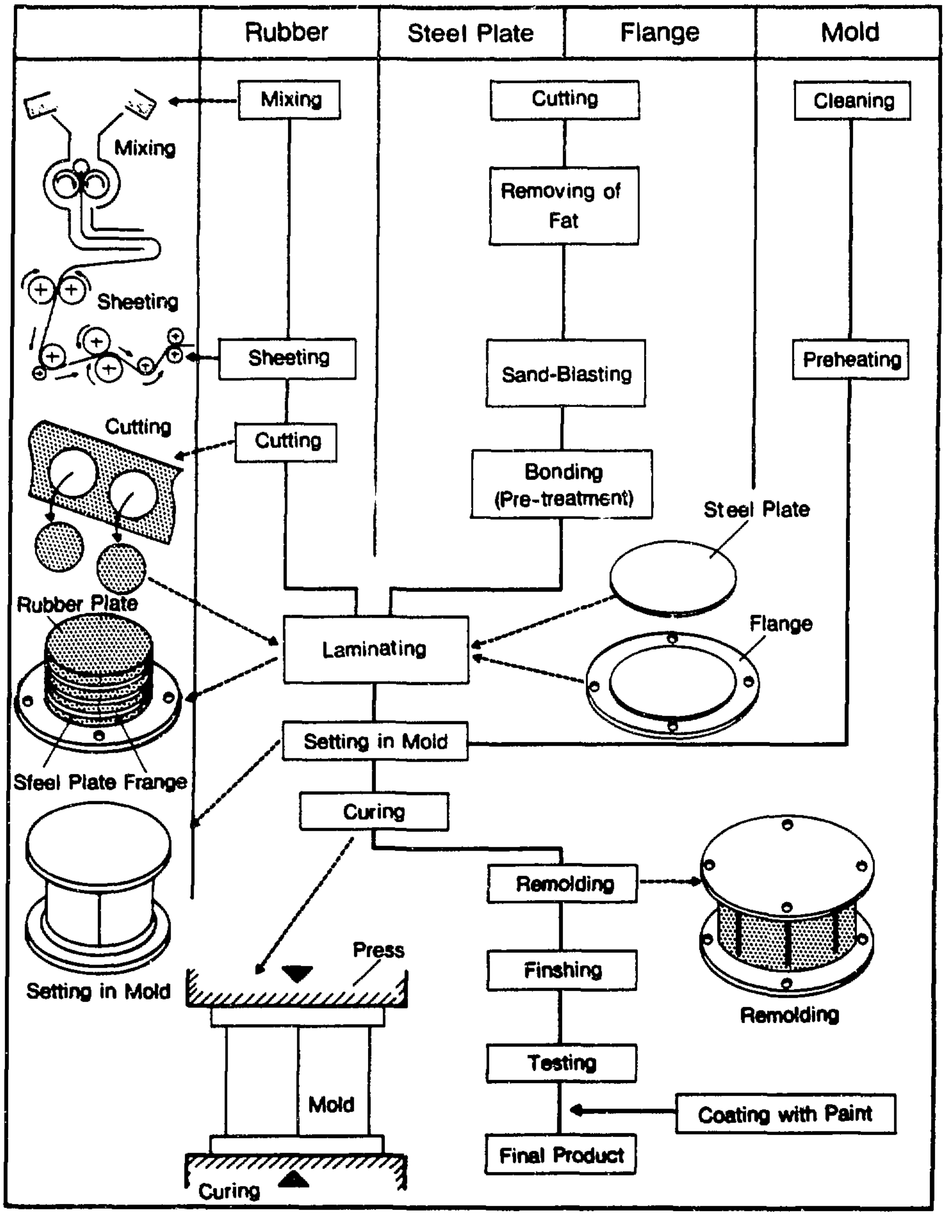


Fig. 22. Manufacturing Process of Rubber Bearing