INVESTIGATION OF AGING EFFECTS FOR LAMINATED RUBBER BEARINGS OF PELHAM BRIDGE

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ABSTRACT

Recently, a number of base isolated buildings using laminated rubber bearings have been constructed in Japan and in the world. In order to improve the reliability of laminated rubber bearings during their serviceable period, it is important to understand their aging characteristics. Although under present conditions, the aging characteristics of laminated rubber bearings are estimated by carrying out heat accelerated aging tests, the relationship between the test results and the actual aging characteristics under natural environmental conditions has not necessarily been made clear. This paper reports on the results of the investigation of the aging characteristics of the laminated rubber bearings of Pelham Bridge in England, which have been used for about forty years. It was found that the region where physical property values changed due to the effects of the air was within 5cm deep from the surface of the laminated rubber bearings while the physical property values in the area deeper than 5cm were almost constant. The increase of the horizontal stiffness of the laminated rubber bearings forty years after the installation was not so much as expected. As compared with the design value, the horizontal stiffness is increased by about 10%.

KEYWORDS

seismic isolation; laminated rubber bearing; aging test; Pelham Bridge; natural rubber; degradation of rubber

LAMINATED RUBBER BEARINGS SUBJECT TO TESTS

Outline of Pelham Bridge Rubber Bearings

Pelham Bridge which is located in Lincoln City about 200km north of London is a road bridge contiguous to Lincoln Station. It was constructed in 1957. A railway runs under the bridge. In order not to restrain thermal elongation of the bridge girders, laminated rubber bearings were introduced. Since the bridge extends south and north and there are footways with a width of about 2m at the outside of the rubber bearings installed at both ends, the rubber bearings themselves are not exposed to the direct rays of the sun except during morning and evening. Moreover, the rubber bearings are seldom exposed to rainwater. Eight units of laminated rubber bearings installed on the steel pier were replaced in 1994. The aging characteristics of two of the eight units were investigated by MRPRA (Malaysian Rubber Producers' Research Association). This paper reports on the results obtained from experiments on the other six units. Photo-1 shows the installation condition of the Pelham Bridge rubber bearings.

Design Specifications of Pelham Bridge Rubber Bearings

The design values of the shape dimensions and the design specifications related to the mechanical characteristics are shown in Table-1 and Fig.-1 respectively. These data are described in the magazine of Rubber Developments(1957). The rubber part with a rectangular section is composed of five layers, each of which has a thickness of 18.4mm and thin layers with a thickness of 6.4mm installed at the upper and lower ends. Since the exterior is covered with rubber, the internal steel plates are not exposed to the air. Upper and lower flange plates are fitted to the laminated rubber bearings with dowel pins. The material is a special natural rubber mix embodying certain anti-ozonants and anti-oxidants. Although tests of vertical and horizontal stiffness were carried out at the production stage , the test data are unknown.

Table-1 Design Specifications Of Pelham Bridge Rubber Bearing

Shape Dimensions	613 × 410 × 181 mm
Rubber Sheets	18.4mm × 5 layers, 6.4mm × 2layers
Vertical stiffness	3.86×10^8 N/m
Shear stiffness	3.86×10^6 N/m
Shore hardness	65-70

Photo-1 Pelham Bridge Rubber Bearing In 1994

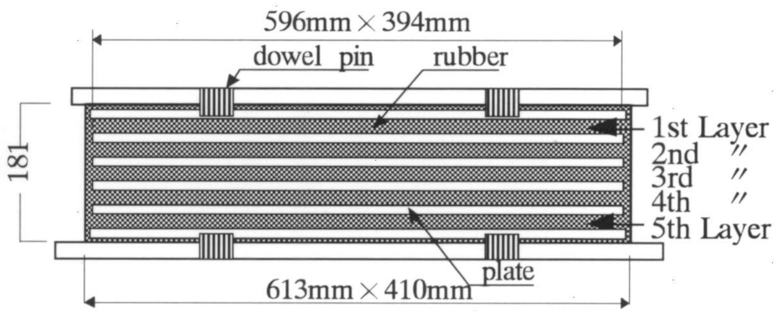


Fig.-1 Cross Section Of Pelham Bridge Rubber Bearing

OUTLINE OF TEST

Tests were conducted on both rubber materials and excitation loading for the laminated rubber bearings in 1995. In the test on rubber materials, the physical properties of the rubber, adhesive strength of the rubber to steel plates and mixture of materials were investigated. In the loading test for the laminated rubber bearings, tests were carried out for vertical stiffness, horizontal stiffness and rupturing characteristics. Fig.-2 explains the relationship between the test items and the numbers of the laminated rubber bearings.

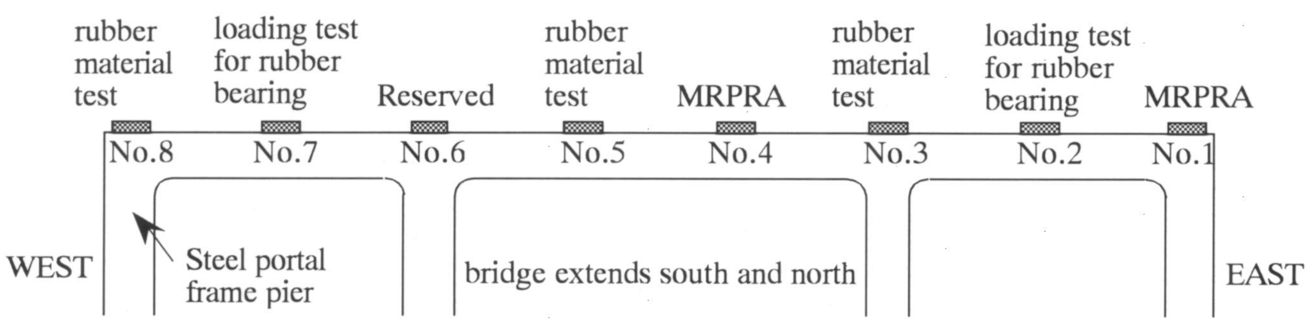


Fig.-2 Number Of Laminated Rubber Bearings Subject To Each Test

Hardness Test and Tensile Test

Test pieces were extracted from the second and the third rubber layers of No.3,No.5 and No.8 rubber bearings. Rubber sheets with a thickness of 2mm were sliced off by 2mm pitches in the area which is 10cm deep from the surface and by 20mm pitches in the area with a depth exceeding 10cm. Dumbbell test pieces as shown in Fig.-3 were cut from the rubber sheets. The rubber hardness of dumbbell test pieces were measured using a spring type hardness gauge. In the tensile test, stress at tensile strain of 100% (hereafter referred to as 100% modulus), ultimate elongation and tensile strength were measured. Fig.-4 illustrates the test results. The value for the hardness and the 100% modulus becomes large in the vicinity of the surface. However, in the area over 50mm deep from the surface, these values are almost constant. The ultimate elongation and tensile strength decrease due to the cracking and deterioration in the vicinity of the surface. However, deterioration of the ultimate elongation and tensile strength is not so large as expected.

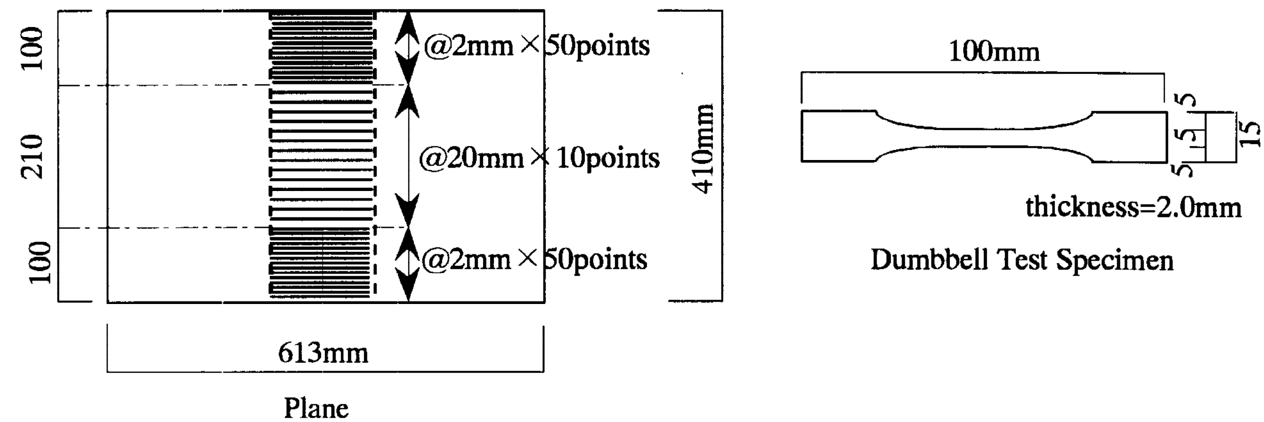


Fig.-3 Test Specimen For Hardness Tests And Tensile Tests

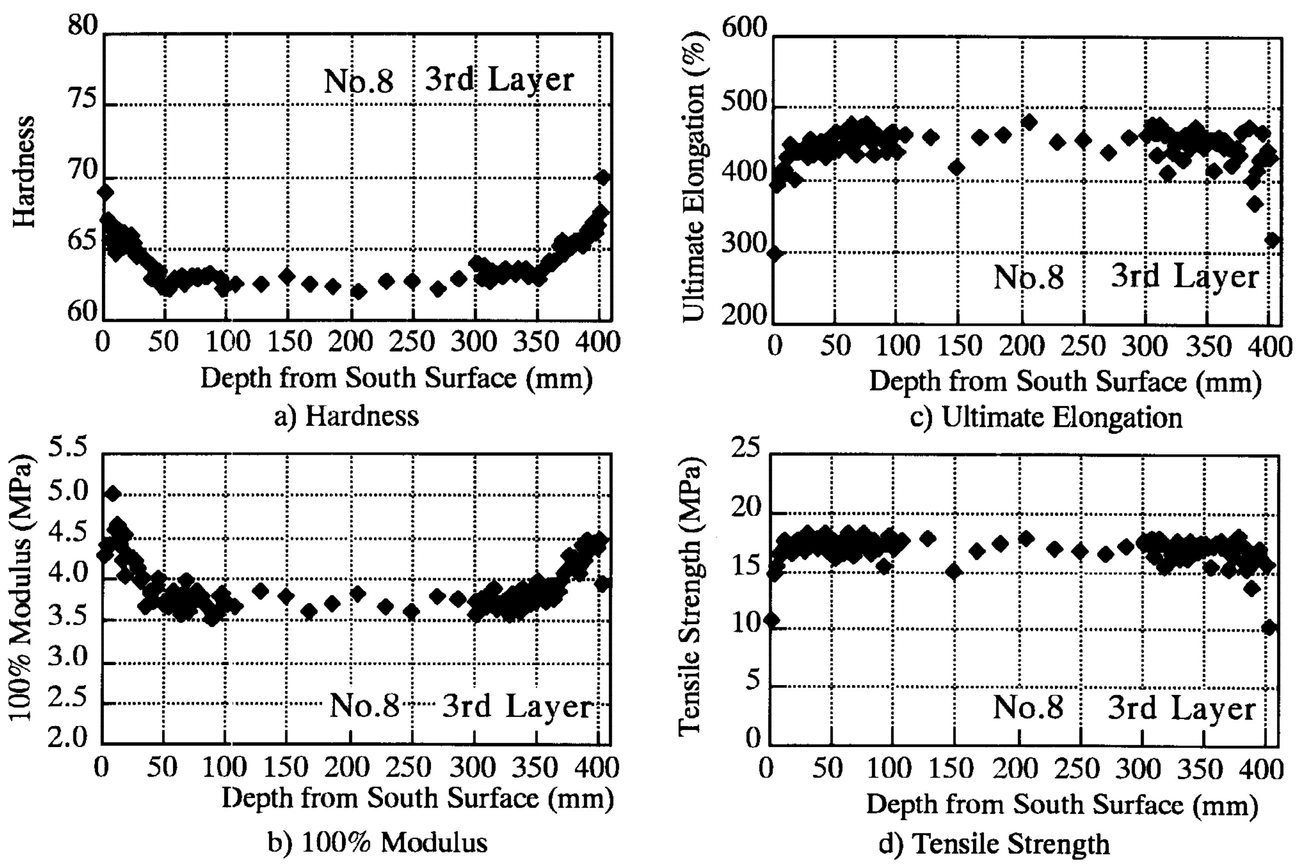


Fig.-4 Relationship Between Physical Properties And Depth From Surface

Fig.-5 shows the relationship between the depth of oxidation and the temperature in the heat accelerated aging test.(Fujita *et al.*, 1995) The depth of oxidation is defined depending on the locations where the physical characteristic values change by 5% or more compared with the value of the rubber in the central part. Fluctuation of the characteristic values in the vicinity of the surface are caused mainly due to the bonding of rubber molecules and oxygen when oxygen in the air diffuses into the inner part of the rubber. In this respect, it can be said that the depth of the area showing a large characteristic change is the "depth of oxidation ". The depth of oxidation depends on the temperatures in heat accelerated aging test, and as the temperature falls, the depth of oxidation increases. The rubber was heated at five levels of temperature from 60℃ to 100℃ in Fig.-5. When extrapolating the depth of oxidation under normal temperature conditions of 20℃ from the test result, 50~100mm is obtained. This result corresponds quite well to the values of the rubber hardness and the 100% modulus shown in Fig.-4.

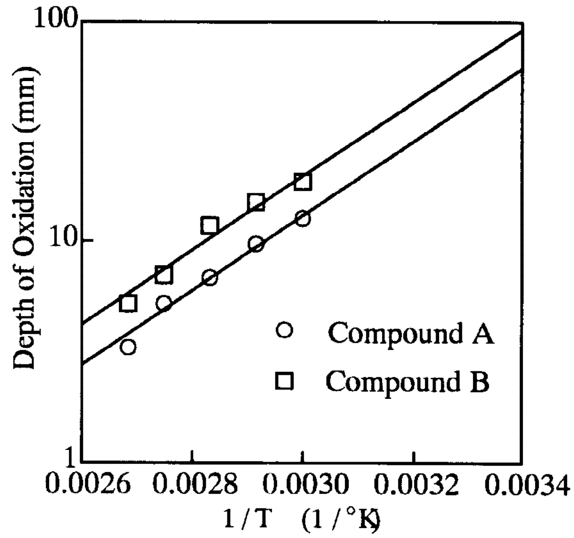


Fig.-5 Relationship Between Depth Of Oxidation And Temperature In Heat Accelerated aging Test (Fujita *et al.*, 1995)

Assuming that the stiffness of the area with a width of 50mm at the surface increases as shown in Fig.-6, the relationship between the diameter of the laminated rubber bearings and the increasing ratio of the horizontal stiffness was obtained. With an increase in the diameter, the influence of change in the stiffness at the surface upon the entire stiffness of the laminated rubber bearings becomes smaller. Therefore, with regard to laminated rubber bearings possessing a large sectional area, it is thought that the stiffness change due to aging effects is induced mainly by thermal aging of the rubber in the internal part. However, since rupture of the laminated rubber bearings starts from the ends of the internal steel plates, it is supposed that the rupturing characteristics are influenced by oxidation deterioration regardless of the size of laminated rubber bearings.

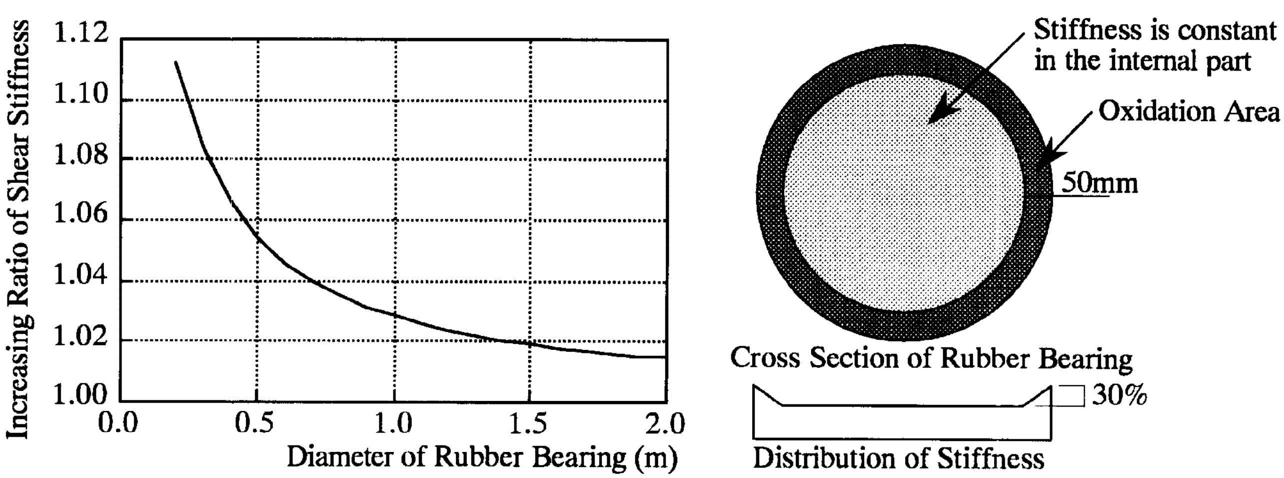
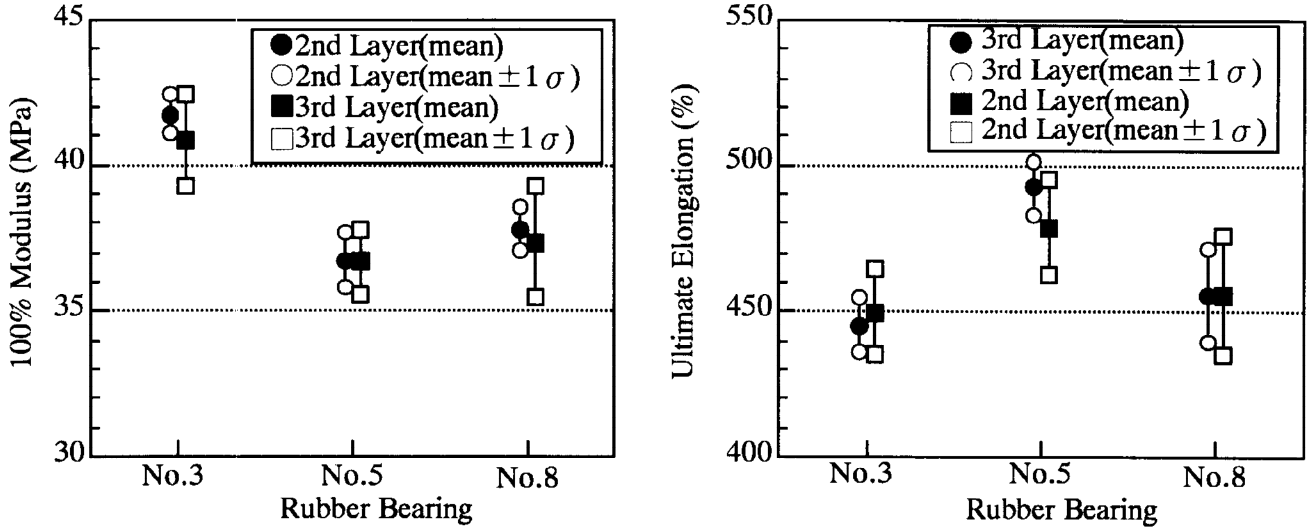


Fig.-6 Relationship Between Diameter Of Rubber Bearings And Increasing Ratio Of Shear Stiffness

Fig.-7 shows the mean and the standard deviation values of the physical characteristics in the area over 50mm deep from the surface. The physical characteristic values of the second and the third rubber layers correspond quite well to each other. Laminated rubber bearing No.8 installed at the west end of the bridge is influenced more greatly by aging than No.5 at the center of the bridge. The physical characteristic value of No.3, which was thought to be most deteriorated judging from the external appearance, are influenced by aging more than the other two laminated rubber bearings.



a) 100% Modulus b) Ultimate Elongation

Fig.-7 Physical Property Values In Area Over 50mm Deep From Surface

Peeling Tests

Peeling test specimens were extracted from eleven points on each of the first and fifth layers for rubber bearing No.5. Adhesive strength was examined by pulling rubber toward a direction of 90° against the steel plate. Monoliquidity adhesive agent was discerned to be used. It was found that peeling occurred on the rubber parts of all eleven specimens extracted from the first rubber layer, and any peelings on the adhesive part were not observed. As for the fifth rubber layer, MC peeling (peeling at the interface between the metal and cement) was discerned for part of the specimens. However, peeling occurred on the rubber parts in the both end specimens of the fifth rubber layer. Consequently, it is thought that the occurrences of MC peeling were not caused by aging effects but due to the fact that the technological level for vulcanization adhesion was lower 40 years ago than at present.

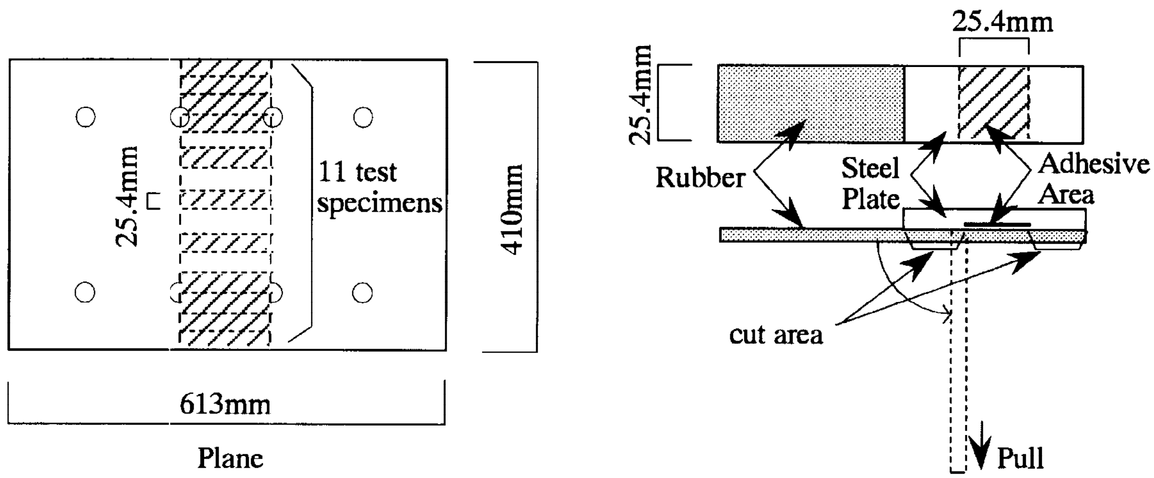


Fig.-8 Test Specimens For Peeling Tests

Shear Failure Tests

In order to investigate the shear modulus and shear failure characteristics for the rubber, five small pieces of test specimens as shown in Fig.-9 were extracted from the third and forth layers of the No.5 rubber bearing. The mean value for the shear modulus is 1.39MPa. The shear modulus is defined using secant stiffness between the shear strain of 20% and 30% which corresponds to the shear strain where the design value of the horizontal stiffness is defined. The shear modulus of the rubber can be calculated from the design value of the horizontal stiffness of the laminated rubber bearings as indicated in equation (1)

$$G = K_h \cdot h_r/A = 3.86\times10^6\times9.2/(59.6\times39.4)\times10^2 = 1.51\text{MPa (Covering rubber neglected)}$$
$$= 3.86\times10^6\times9.2/(61.3\times41.0)\times10^2 = 1.41\text{MPa (Covering rubber considered)} \quad (1)$$

The shear modulus in the inner part measured 40 years after the completion of the bridge is slightly smaller than the design value. There may be some differences between the design stiffness and actual stiffness of the manufactured rubber bearings. It can be concluded that the increase of shear stiffness caused by aging effect is not so large. The mean value for the shear strain at rupture is 281%. In all five specimens rupture occurred on the rubber parts. It is thought that shear strain at rupture doesn't decrease due to the aging effect for the adhesion agent.

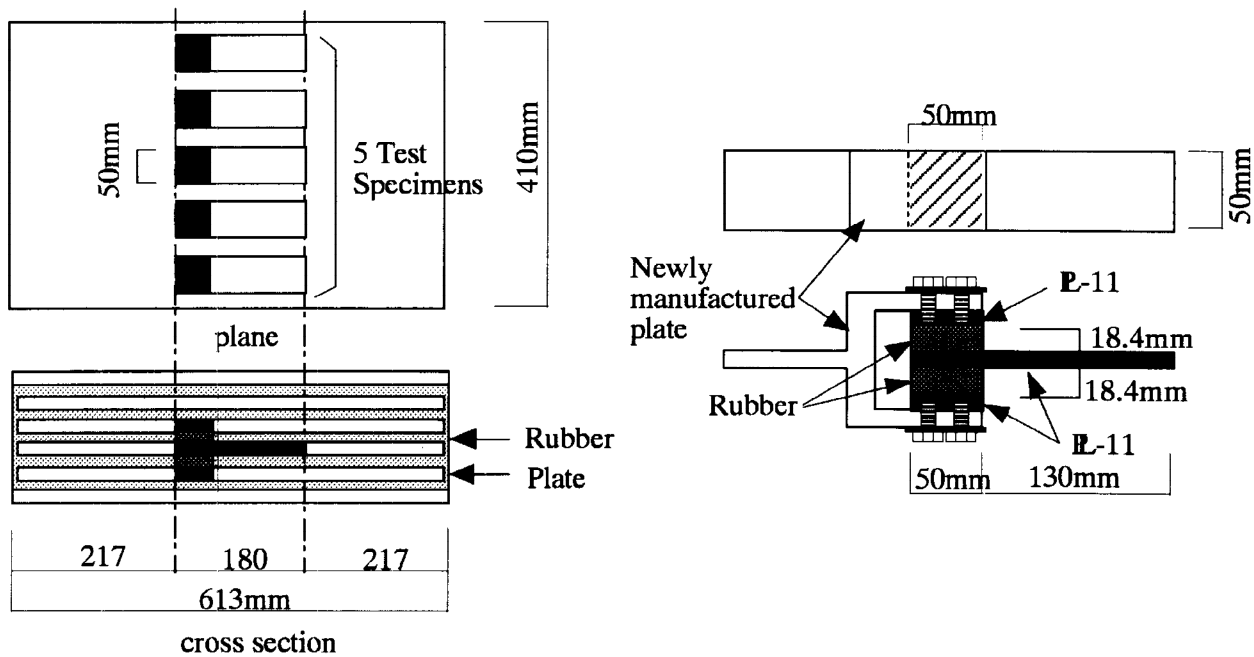


Fig.-9 Test Specimens For Shear Failure Tests

Mixture Analysis Tests

Mixture analyses were conducted for the pieces of rubber of the second and third layers for laminated rubber bearings No.3, No.5 and No.8. Measurements were carried out at five points for each layer. The test results are shown in Table-2. The natural rubber is used. The mix proportion ratio of carbon black and ZnO is higher than that for present laminated rubber bearings. Antioxidant of amine compound was detected from the rubber. There is not a large difference between mix proportion of the Pelham Bridge rubber bearings and that of present laminated rubber bearings. The oxygen content is shown by superposing it on the 100% modulus values in Fig.-10. The oxygen content shows a higher value in the surface than in the central part. The oxygen content value in the central part coincides with the calculated value by summing up contents of the oxygen contained in the natural rubber, ZnO, fatty acid and etc. according to the test results of the mixture analysis. Therefore, it is thought that the increase of oxygen in the vicinity of the surface was caused by diffusing of oxygen in the air. The oxygen content value profile and the tendency of the 100% modulus values are in good agreement with each other. On the contrary the content value of antioxidant is smaller in the vicinity of the surface than in the internal portion, because antioxidant in the vicinity of the surface was consumed by oxygen.

Table-2 Mixture Analysis Results (weight %)

Rubber Bearing	No.8 (Third Layer)		
Depth from South Surface	3mm	100mm	200mm
Polymer (Natural Rubber)	52.7	52.4	52.0
Acetone Extraction	4.7	4.6	4.3
Plasticizer	not found	not found	not found
Total Surfer	1.7	1.8	1.8
Combined Surfer	1.6	1.6	1.6
Carbon Black(SRF class)	28.6	28.5	28.1
Ashes*1	12.4	12.9	14.0
Antioxidant*2	0.3	1.6	1.6
Fatty Acid	0.8	0.6	0.6
Accelerator	CBS or CMBT	CBS or CMBT	CBS or CMBT

*1 Major component is ZnO. Infinitesimal quantity of K, Ca and S was found.
*2 Major component is N,N'-bis(1 ethyl-3 methyl penthyl)-p-phenylendiamine

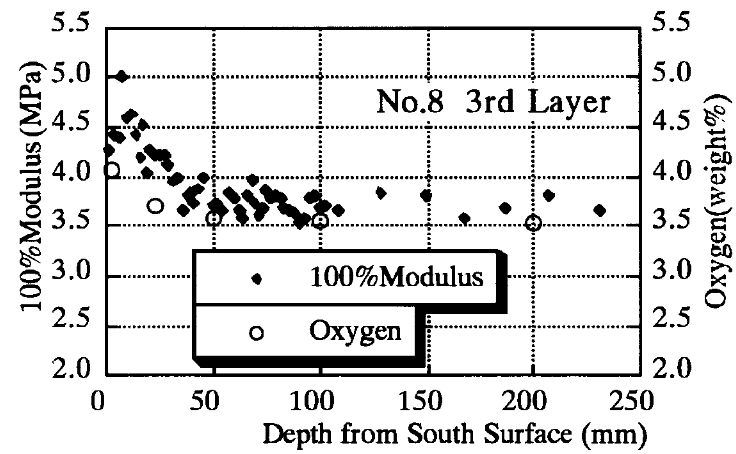


Fig.-10 Relationship Between Oxygen Content Value And 100% Modulus

EXCITATION LOADING TESTS FOR LAMINATED RUBBER BEARINGS

Loading Test Method

Excitation loading tests were conducted for laminated rubber bearings No.2 and No.7. With the aim of carrying out shear failure tests, after removing the upper and lower flange plates connected with dowel pins and the upper and lower rubber layers with a thickness of 6.4mm, newly manufactured flange plates were fitted to the laminated rubber bearings using bolts. First, the vertical stiffness and horizontal stiffness were examined. In the vertical stiffness test, an axial force of 1.96×10^6N was imposed in the same way as the initial loading test condition described in the magazine of Rubber Developments(1957). In the horizontal stiffness test, under the condition of imposing an axial force of 5.88×10^5N ,which corresponds to the assumed static load of the bridge bearing, loading was made with a displacement amplitude of ± 2.8cm($\gamma = \pm 30\%$). After these tests, under the condition of imposing an axial force of 5.88×10^5N, a shear failure test was made in a long side direction.

Loading Test Results

The vertical stiffness in case of an axial force being 1.96×10^6N is 5.23×10^8N/m. The design value of the vertical stiffness is 3.86×10^8N/m. Under the consideration of the fact that the thickness of the rubber layer becomes thin by 12% by removing the rubber layers with a thickness of 6.4mm, it is found that the vertical stiffness increases by approximately 20% of the design value due to aging effects.

The horizontal stiffness when the shear strain is ±30% was 4.21×10^6N/m for laminated rubber bearing No.2 and 4.30×10^6N/m for No.7. The test result of the horizontal stiffness is about 10% larger than the design value 3.86×10^6N/m.

Fig.-11 illustrates the hysteresis curve. When the shear strain is ±100%, a stable hysteresis curve is generated. Both No.2 and No.7 began to be ruptured at the shear strain of 160%. On No.2, rupture occurred at the adhesive part. As for No.7, rupture broke out at the interface between adhesives and the plate.

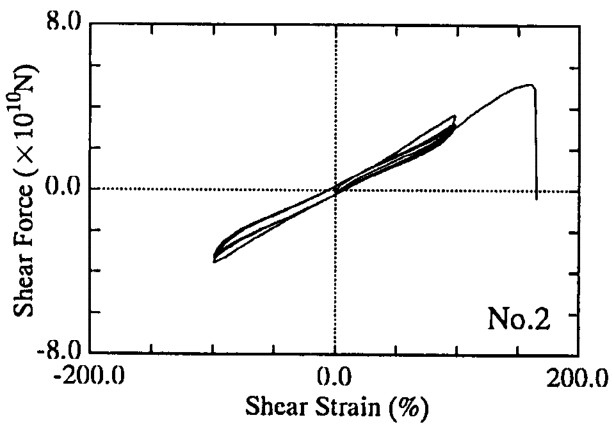


Fig.-11 Hysteresis Curve Of No.2 Rubber Bearing

CONCLUSION

As a result of investigations for the characteristics of aging effects of the forty year old laminated rubber bearings installed on Pelham Bridge, the following were made clear.

1)The increase of the horizontal stiffness of the rubber bearings forty years after the installation is not so much as expected. As compared with the design value, the horizontal stiffness is increased by about 10%.

2)The physical characteristic values of the rubber change in the area expanding from the surface to the depth of about 50mm, but it is constant in the deeper area.

3)With regard to laminated rubber bearings possessing a large sectional shape such as those used for base isolated buildings, since an oxidation domain covers only a small part of the entire sectional area, oxidation-induced increasing of the shear stiffness of the laminated rubber bearings can be neglected. Change of stiffness with aging is caused mainly by fluctuation of the characteristics of the rubber at the central part.

4)When estimating activation energy in heat accelerated aging tests, an estimation must be made on the basis of results obtained from tests of rubber in which an influence of oxidation can be neglected.

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