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EXPERIMENTAL STUDY ON BASE-ISOLATED BUILDING USING LEAD RUBBER BEARING THROUGH VIBRATION TESTS

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SUMMARY

The results of vibration tests of the Oiles Technical Center Building, a 5-story, reinforced concrete, base-isolated structure using 35 Lead Rubber Bearings (LRBs), and the results of experiments on the characteristics of the LRBs of this building, will be discussed in this paper. The fundamental frequency of the building, the damping ratio as affected by the LRBs, the vibration mode etc. were investigated by free vibration testing and forced vibration testing. The results of these tests verified the fundamental vibration characteristics of the base-isolated building.

INTRODUCTION

The Oiles Technical Center Building, the TC building of the Oiles Corporation (Fig.1), received special authorization from the Minister of Construction, based on the provisions under Artile 38 of the Building Standards Law of Japan. This was the first base-isolated building built in Japan equipped with Lead Rubber Bearings (LRBs). The TC Building was completed in February 1987. It has a total floor area of approximately 4,800m ^{2} and a total building weight of 7,500 tons being the largest base-isolated building in Japan at present.

The LRB base-isolation system (Refs 1-3) was developed by the Physics and Engineering Laboratory of the New Zealand, Department of Scientific and Industrial Research. The technology was licensed to Japan in 1983. In New Zealand, the LRB has been used in over 30 bridges and one building.

These tests were planned primarily to verify the reliability of the base-isolated building under an earthquake. The tests consisted of free vibration tests, forced vibration tests and microtremor observations. Appropriateness and accuracy of analysis method were also verified.

<u>Design concepts</u> The following criteria were set as targets; (1) to reduce the deformation of building members to enable them to remain within their elastic range, thus protecting the structure from even minor damage during an earthquake, (2) to decrease the response acceleration of each floor, thus ensureing the safety of the contents of the building including its personnel and facilities etc. during a severe earthquake. For these targets, the design velocity of the ground motion was assumed to be 50 cm/sec. For the safety of the whole structure, 75 cm/sec velocity was also assumed.

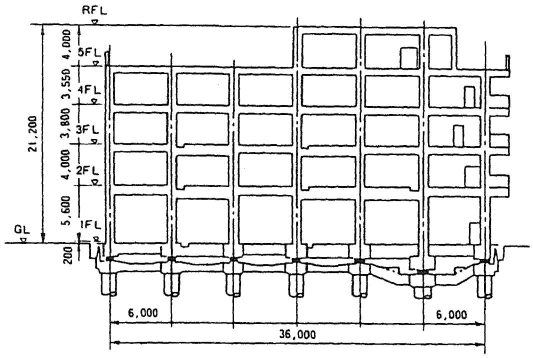

Fig.1 Elevation of TC Building

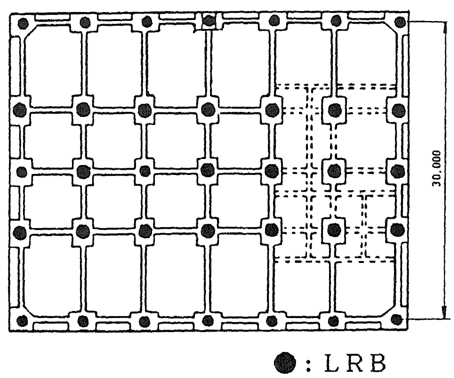

Fig.2 Plane View
and allocation of LRBs

Building Design and Construction Details The earthquake motion waves used for the dynamic analysis were El Centro 1940(NS), Taft 1952 (EW) and Hachinohe 1968 (NS & EW) as standard specific seismic waves. The results of dynamic analysis showed that the response acceleration of each floor of the building was reduced to about 200 gal even during strong earthquakes (300-500 gal) at an input of 50 cm/sec. The maximum response acceleration was reduced to between 200 and 300 gal even under the velocity of 75 cm/sec. The shearing force for each story was shown to be less than the yielding force, while the maximum response displacement was 37 cm. The actual design was, however, made in the same way as that for non-base-isolated one, with designed base shear force coefficient of 0.2, and distribution coefficient of shearing force for each floor to be 1.0. These were based on the existing building code in Japan.

The TC Building is a 5-story reinforced concrete frame structure with 30 m x 36 m plan dimensions. 35 LRBs were installed, one under each column of the building. Fig.2 shows the arrangement of LRBs. Based on the preliminary tests, each LRB was allotted dispersedly according to its specific stiffness to ensure the minimization of dissociation between the building gravity center and the LRBs' stiffness center. As a result, both center are to be almost overlapped on the plan view.

Bearings LRBs are elastic bearings with energy absorbtive function. They are laminated elastomeric bearings with lead plugs. Cylindrical lead plug is pressed into the hole of each bearing. Horizontal force is transmitted by the dowel pins between the bearing and connecting plates. Fig.3 shows typical cross-section of the LRB. The base-isolation system installed in the TC Building consists of 35 units of LRBs with 4 different diameters from 650 mm to 800 mm.

The lead plug is deformed by shearing force when LRBs are deformed by horizontal force. The energy required for plastic deformation of the lead plug is consumed as vibration damping energy reducing the relative displacement between the building and the ground. The deformation characteristics of LRBs are nearly bilinear, as shown in Fig.4. A idealized bilinear curve, as shown in Fig.5 is used in the dynamic analysis of the whole system.

The total rubber thickness of a LRB is designed to have a shearing strain less than 200% against 75 cm/sec velocity earthquake deformation, and less than 100% against the deformation at 50 cm/sec earthquake. Each LRB consists of 24 layers of rubber 10 mm in thickness.

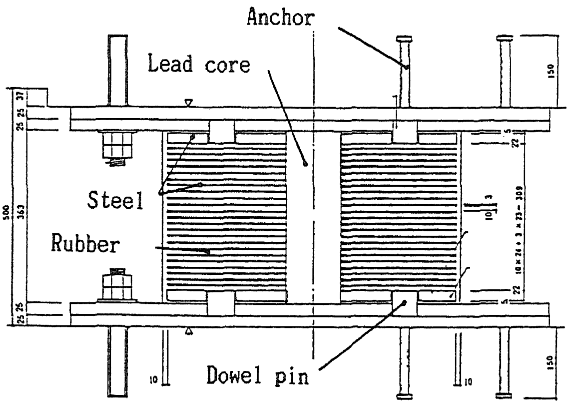

Fig.3 Cross Section of LRB

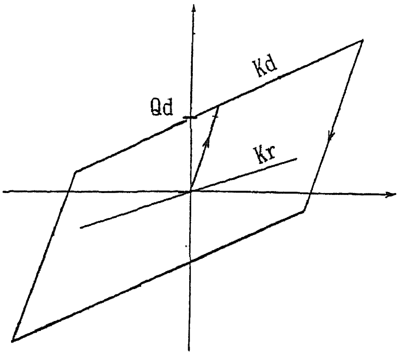

Fig.5 Idealized Bilinear Curve of LRB

LRB PERFORMANCE TEST RESULTS

Every LRB was tested to confirm its characteristics of each bearing such as horizontal stiffness, vertical stiffness and yielding load of the lead plug.

The combined hysteresis loop of the 35 LRBs is shown in Fig.6. From this hysteresis loop we conclude that for a strain of 50%, the measured yieled strength is 2% higher than the design value while the post elastic stiffness is 14% less than the design value. These values were to be considered as sufficiently allowable and justified the use of these LRBs in the TC building.

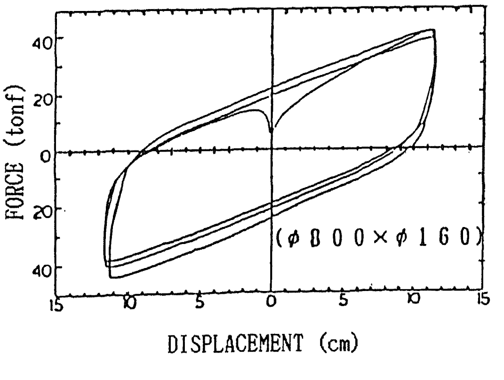

Fig.4 Typical Hysteresis of LRB

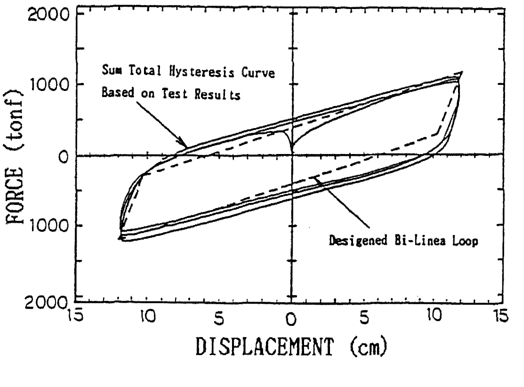

Fig.6 Comparison of Hysteretic Curve (Designed and Tested Results)

VIBRATION TESTS

Vibration tests were carried out on the actual TC Building to investigate base-isolation performance and to comfirm vibration characteristics by the artificial application of external forces.

Free Vibration Tests Two hydraulic jack units, with a capacity of 300 tons each, were attached to the top of a foundation pile, and two cables, each 63.5 mm in diameter, were attached to join these jacks to a first floor beam in the building. The lower section of the building was pulled by wire via a coupling rod of precalculated breaking strength and vibrations of the building were measured when the breakage of the coupling rod released the building from the pulling wire.

Various amounts of displacement were applied in a series of free vibration tests. The maximum displacement applied was approximately 40 mm, with the tensile force being approximately 400 tons. Continuous measuring of the tensile forces and displacements in the process made it possible to grasp the charasteristics of the restoring force of all 35 LRBs. Fig.7 shows the relations of force and deformation while the applied horizontal force is increasing to the breaking point. Only in the test No.Fs 4-0 the horizontal force was increased to just before breaking point, then decreased to zero. The strain velocity used in applying this deformation to the bearing was approximately 4×10^{-5} /sec, which is 10^{-3} to 10^{-5} times smaller than that expected at an earthquake. The relations between strain velocity and shearing yield force of lead was reported in the paper by Dr.W.H.Robinson of DSIR(Ref.2). From this, the yielding stress of lead at the strain velocity of 4×10^{-5} /sec was estimated as being 50 Kgf/cm ^{2} . A portion of the calculated hysteretic curve is shown by the broken line in Fig.8. This closely matches the results obtained from the testing.

Fig.8 shows the time-history data of relative displacement between the foundation and the first floor and acceleration of the building at the 42 mm displacement test. Fig.9 shows the transmission function obtained based on the data of acceleration and tensile force. It was observed that when the amount of displacement increased and the shear strain of the bearing exceeded 12.5%, the so-called "first base-isolation mode"appeared. The first fundamental frequency at this moment decreased to approximately 1.5 Hz from around 2.3 Hz, which was supposed to be the first fundamental frequency of the non-base-isolated building. The damping ratio which was assumed to be between 3% and 5.5% in the non-isolated state increased to approximately 30%, indicating the contribution of the LRBs to damping.

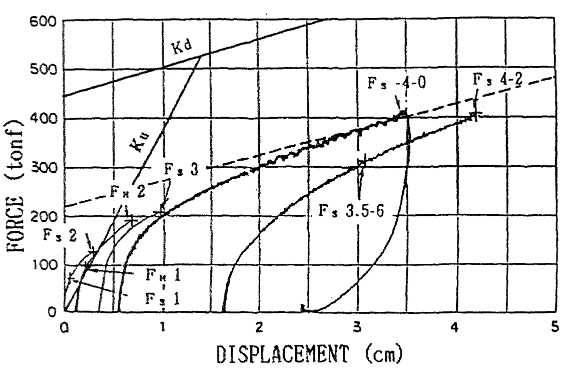

Fig.7 Forced – Displacement Curve of 35 Bearings

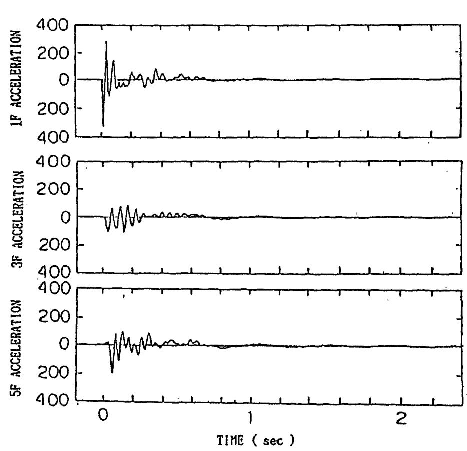

Fig.8 Time–History (Displacement of 42 mm)

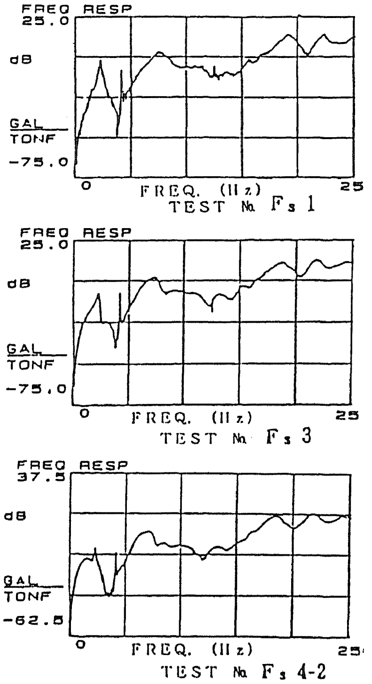

Fig.9 Transmission Functions in Free Vibration

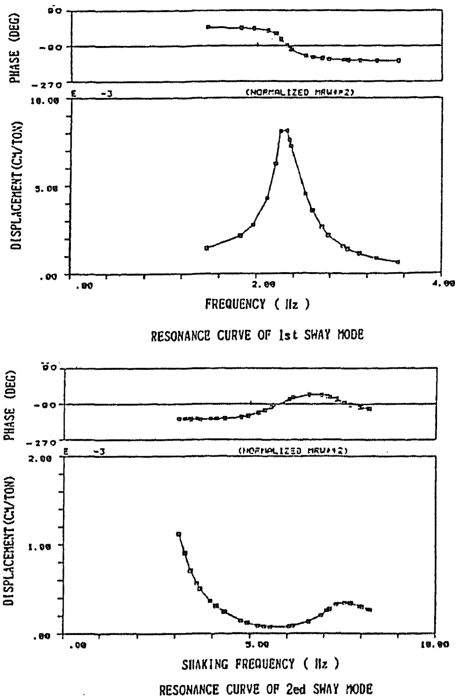

Fig.10 Resonance Curves (1st and 2nd)

Forced Vibration Tests Sine wave vibration was applied using a pair of vibration generators installed on the 5th floor (RF) of the building. The amount of deformation by forced vibration tests is very small compared to that of free vibration tests. Therefore, the proper vibration frequency and damping ratio, which would be determined by the initial rigidity of the base-isolation system, were investigated through frequency response function.

Fig.10 shows the displacement resonance curves for the first and second sway mode. The following were clarified through the forced vibration tests. The resonance frequency of the first sway mode in the direction of the shorter side of the building was 2.30 Hz, and the vibration mode of the building at that time was the mode in which all floors, from the first floor to the 5th (RF) floor, were moving in the same direction. The resonance frequency of the second sway mode was 7.30 Hz. The vibration mode of the building at this time was the one in which the first floor and the fifth floor moved in reverse direction.

We clarified the fact that the damping ratio was approximately 6% at the LRB strain level of 0.05% according to the results of calculation using the 1/2 method from the resonance curve of first sway mode. The damping of second sway mode at the LRB strain level of 0.05% was clarified as being approximately 6% to 10%.

Microtremor Measurement The vibration characteristics of the ground on the site, and the microtremor transmission characteristics were also investigated. According to the observed data of constant microtremor, the maximum displacement, in the horizontal direction of the first floor was approximately 2.0×10^{-3} mm, and the LRB shear strain level was approximately 4.0×10^{-6}

The fundamental frequencies of microtremor of the TC building were judged from the peak values in the Fourier spectrum. The frequencies were 2.4 Hz for the shorter side (X direction)of the building, and also 2.4 Hz for the longer side (Y direction)of the building. The microtremor damping ratio was calculated as approximately 4% according to the Fourier spectrum and the 1/2 method using transmission function.

CONCLUSIONS

Horizontal strain applied to the LRBs in these tests was relatively small at less than 20%. This strain value range was not sufficient enough to realize longer fundamental period where the building was to be base-isolated. The followings, however, have been clarified from the results of these vibration tests, and from the results of single-performance testing of LRBs.

The characteristics of a single LRB and of the 35 LRBs units as a whole installed in the building were in good accordance with each other. These were almost the same as the design values, thus the appropriateness of LRB design was confirmed. These tests proved the relations between displacement and the fundamental period in the LRB base-isolated building. Important data were also obtained to form a model of LRB hysteresis characteristics for vibration systems. A damping ratio of 4% to 7% for LRB installed building was confirmed for strains below 10^{-3}.

A damping ratio of approximately 30% was determined from the free vibration tests for strains of 10%. These results coincide with those of single LRB test. Therefore, it is assuredly believable that the damping ratio, as designed, can be achieved even under the deformation strain of 50% to 100% which may occur at the time of a severe earthquake.

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