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DESIGN AND ITS PERFORMANCE VERIFICATION OF A BASE-ISOLATED BUILDING USING LEAD RUBBER BEARINGS IN JAPAN

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SUMMARY

The goal of this study is to realize buildings which can withstand very strong earthquakes without any damage. A five story Base-Isolated Building using LRB was designed and constructed. The analysis method was verified by comparing the designed dynamic characteristics with ones obtained from LRB tests, free and forced vibration tests and microtremor measurements of the building. Observed earthquake records also indicate the accuracy of the design and LRB performance.

INTRODUCTION

The Technical Center Building is the first structure which used Lead Rubber Bearings (LRB:laminated rubber bearing with lead plug) in Japan. This is the second newly built LRB base-isolated building in the world. The first is the William Clayton Building[1)] in N.Z..

The construction work started in April 1986, and was completed in February 1987, at Fujisawa, Kanagawa pref., west of Tokyo. 35 LRB were manufactured in Japan. All of them were tested before installation. After construction, free and forced vibration tests were carried out, and microtremors were observed[2)]. On March 18th 1988 fairly good acceleration records were obtained from the Tokyo-to Tobu Earthquake(M=6.0).

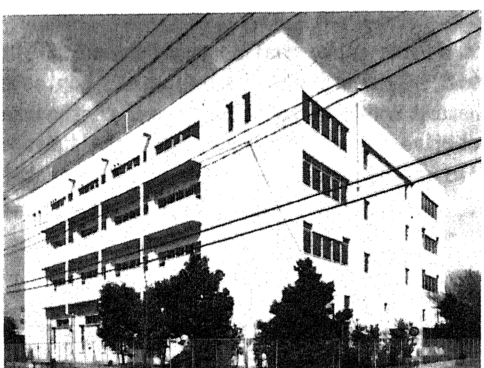

Photo 1 Out View of the Technical Center

This building was designed to achieve very high safety against quite strong earthquakes. This paper presents the response analyses of this building, and shows the effectiveness of 'LRB base-isolation method' by comparing the analyses results of the base-isolated model with ones of the non-isolated. By comparing the dynamic characteristics of the designed values with the tested or observed ones, the performance of LRB and the response analysis method are examined.

BUILDING DESCRIPTION

The Technical Center Building is a five story reinforced concrete rigid frame structure with shear walls, and has plan dimensions of 36×30m with column grid lines at 6.0m & 9.0m. This building is mainly used as a technical research office, and includes computer rooms and a machine laboratory. Its total floor area is 4800m^2, and the total weight of 7500tons is supported by LRB. The 35 cylindrical shaped LRB were installed, each under every column between the first floor and its foundation. The diameter of the LRB are from 650mm to 800mm supporting 200~400tons of vertical weight. Each LRB sits on a foundation supported by 1200mm ~ 1600mm diameter cast-in-place concrete piles reaching the stiff soil layer at GL-15.0m. The haunched beams and 200mm thick mat-slabs connect all foundations to restrict the pile top rotation and to provide the horizontal rigidity.

Based on the Building Standard Law of Japan, this building was designed with a base shear coefficient of 0.2: the same value as that of non-base-isolated conventional buildings. This value was decided based on the dynamic response analyses with the maximum ground velocity 50cm/s. This aims at realizing high seismic safety - without any damage even from very strong earthquakes, without adding extra reinforcement to the conventional frames.

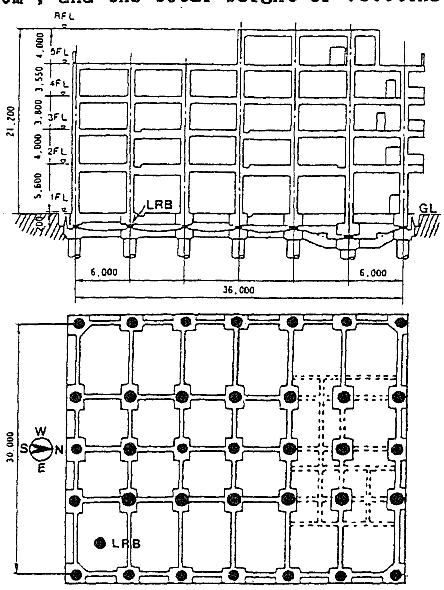

Fig.1 Plan & Section of T.C.Bldg.

DESIGN GOAL

In Japan, all buildings have to satisfy the earthquake resistant regulations called "New Aseismic Design Method for Buildings" of the Building Standard Law of Japan.
The criteria of this regulation are as follows ; ① Buildings shall withstand moderate earthquake motions, which would occur several times during the use of the buildings, with almost no damage. ② Buildings shall not collapse nor harm human lives during severe earthquake motions, which would occur less than once during the use of the buildings.

On the other hand, the design goal of this building is to realize much higher safety against very strong earthquake motions as follows ; ① Buildings, including all contents (equipments,accomodations and humans), shall withstand moderate and also severe earthquake motions without any damage. ② Buildings shall not give any anxiety to people, shall avoid panicking people, and shall preserve their economic values even in very strong earthquake.

ANALYSIS MODELS

Figure 2 shows two types of inelastic time history analysis model used for the design of this building. Each story's inelastic stiffness of the Model-A(mass and shear-spring model) was represented by a degrading tri-linear curve. These skeleton curves are based on the relationships between story shear and interstory drift, obtained from the static inelastic frame analysis applying incremental lateral loads. Frame models(Model-B) were used to evaluate the behavior of each LRB, especially to grasp the maximum vertical forces acting on LRB, and the vertical up-lift of LRB's anchor-pins.

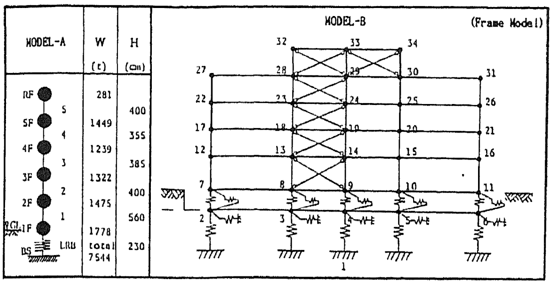

Fig.2 Dynamic Analysis Models

Figure 3 shows the horizontal design hysteresis loops provided by all 35 LRB. The hysteresis loops of LRB show considerable strain dependence. Taking account of this characteristics is very important for an accurate dynamic response evaluation of base-isolated structures by LRB. The authors named this method " Modified Bi(Tri)-Linear Loop for LRB", because the bi(tri)-linear loop is changed at the time step when the LRB experiences the maximum lateral deformation.

The vertical stiffness of the LRB shown in Fig.4 is described by an asymmetrical bilinear curve tracing back on this line without energy absorption, in order to evaluate the uplift of LRB's anchor-pins. These inelastic time history analyses reflecting the strain dependence of LRB were carried out by a computer program developed by the authors.

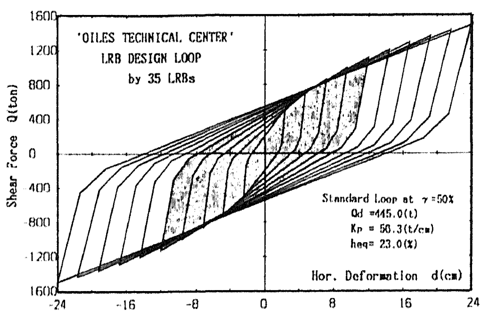

Fig.3 LRB Design Hysteresis Loops reflecting on the strain dependence

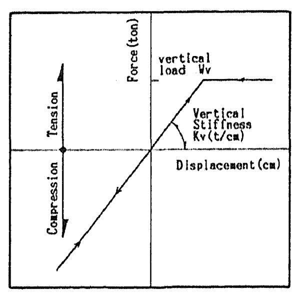

Fig.4 Vertical hysteresis curve of LRB

RESPONSE ANALYSIS RESULTS

Acceleration Response Figure 5 shows the maximum response acceleration at each floor of the Base-Isolated and the Non-Base-Isolated Model excited by Vmax=50.0cm/s earthquakes motions. The maximum value of 1174cm/s^2 in the Non-Base-Isolated model is reduced to 223 cm/s^2 in the Base-Isolated Model. The maximum response acceleration is reduced to about 1/2 ~ 1/6 by this isolation system, and the frames can survive without damage. Another feature of this Base-Isolation is that the maximum response accelerations are almost the same (about 200cm/s^2), depending neither on the floor levels, nor the input waves.

Figure 6 shows a comparison of the maximum response accelerations, depending upon the input intensity level of the El Centro NS(1940). This isolation system shows the better performance in the stronger input excitation. The non-isolated frames will be severely damaged in stronger input than the maximum ground velocity 25cm/s.

Displacement Response Figure 7 shows the maximum response displacements relative to the foundations, excited by Vmax=50.0cm/s earthquakes. Maximum deflection of LRB is 11.8cm ~ 24.4cm. The maximum value occurred by artificial wave AW-3 for soil type-3 (for site on soft soil layer). These values cause a max. shear strain of 49.2% ~ 101.7% to the rubber, and exactly conform to the design criteria of 50~100 % for severe earthquake motions. The construction site belongs to soil-type 2, and the maximum deformation by AW-2(for soil type 2) is 22.0cm; shear strain γ =91.7%.

Figure 8 shows the maximum response displacements, depending on the input intensity level of the El Centro NS(1940). The deformation of LRB is greatly influenced by the input level, but the max. value is only 21.7cm(γ =90.4%) in the case of the max. ground velocity 75.0 cm/s(Amax=766.2 cm/s^2).

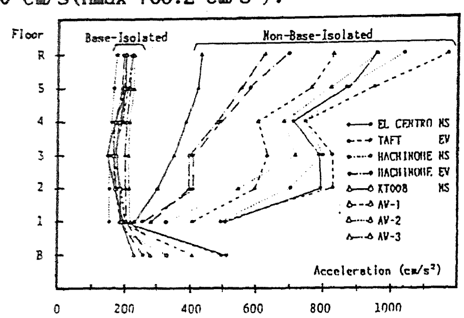

Fig.5 Max. Response Acceleration at each floor(Vmax=50.0 cm/s)

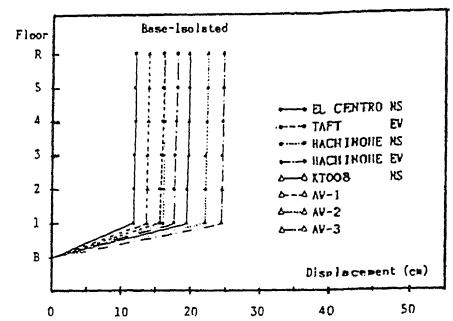

Fig.7 Max. Response Displacement at each floor (Vmax=50.0cm/s)

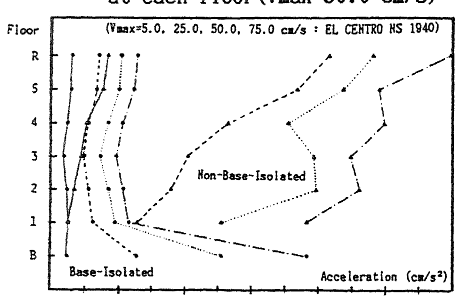

Fig.6 Comparison of Acc. Response and Input Intensity Level

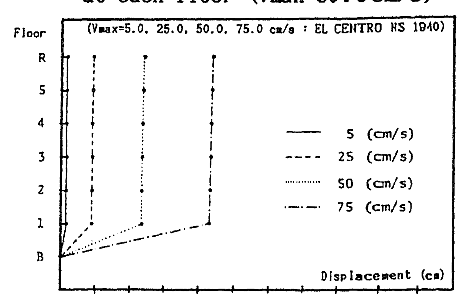

Fig.8 Comparison of Disp. Response and Input Intensity Level

LRB HYSTERESIS CHARACTERISTICS

Table-1. Hysteresis characteristic values of 35 LRBs

(at 50% strain)	Qd (ton)	Kr (t/cm)	Kd (t/cm)	K_{eq50} (t/cm)	Kv (t/cm)
Designed Value	438.0x0.9	45.5	65.8	98.8	49656.6
Tested Value	445.0	51.0	56.3	93.4	51717.9
(mean value)	14.4	1.46	1.61	2.67	1477.7
(T.V.)/(D.V.)	1.02	1.12	0.86	0.95	1.04

Table-1 shows the totaled characteristic values of all of 35 LRB. Designed values of yield characteristic strength: Qd, vertical stiffness: Kv and equivalent stiffness: Keq showed very good approximation to the tested values.

The rubber stiffness Kr, and the post-elastic stiffness Kd showed a 12~14% difference from the designed values. But the tested values are preferable as isolators. Based on these data, the LRB's characteristics can now be evaluated very precisely.

FUNDAMENTAL FREQUENCIES, DAMPING CONSTANT AND VIBRATION MODES

Fundamental frequency of the building was measured by 4 different methods, i.e., free & forced vibration tests, microtremor & earthquake observations. Figure 9 shows the comparison of the 1st mode frequencies between the designed values & the measured ones. Designed Value line is a frequency curve determined by the diagonal stiffness Keq of the LRB design loops corresponding to the shear strain. Measured frequencies were confirmed to be identical with the designed values in strain level $\gamma \leq 20\%$.

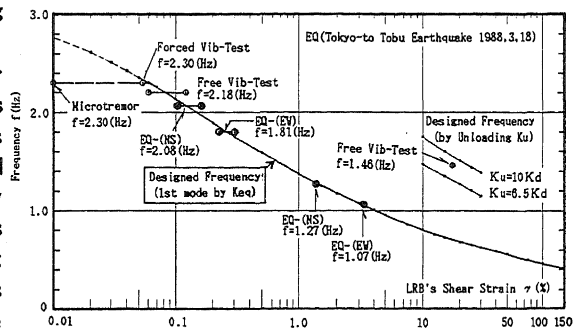

Fig.9 Measured 1st mode Frequency

Figure 10 shows the measured damping constants h and strain level γ. Damping constant h of the design loops ranges from 23% to 20% in strain level γ = 0.5~150%. Higher values were obtained from all tests and observations. Even in a very small strain level, this building shows a quite high damping constant.

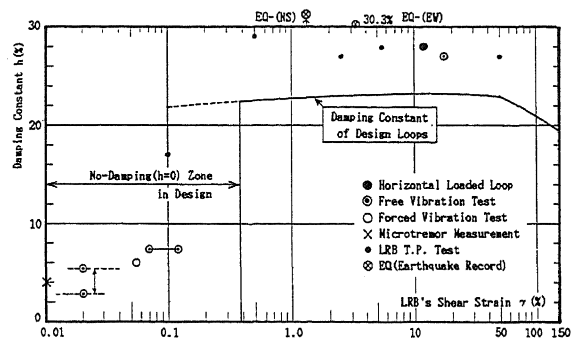

Fig.10 Measured Damping Constant h

Figure 11 shows 1st. & 2nd. vibration modes obtained by forced vibration test. Because of the low strain level (γ = 0.05%), the mode has not grown to a typical mode as an isolated building. This is because of LRB's high stiffness in a small strain region. The vibration mode changes as LRB experience the larger strain. Figure12 illustrates the transform of the 1st mode depending on LRB's strain level.

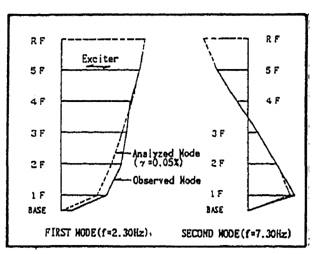

Fig.11 Measured Modes

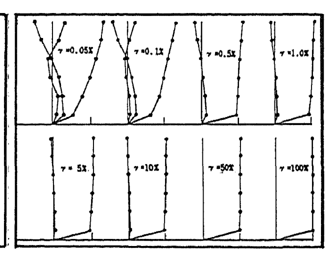

Fig.12 Mode-Strain γ

EARTHQUAKE RECORD AND ITS SIMULATION

On March 18th. 1988, the Tokyo-to Tobu Earthquake(M=6.0) occurred. The earthquake observation system with almost 90 channels of the building recorded its strongest accelerograms so far. The maximum acceleration at foundation was 61.6(EW) and 57.1cm/s2(NS). Figure 13 illustrates the recorded maximum acceleration values in an EW direction. On the 2nd floor of a neighboring base-fixed building, 83.4cm/s^2 was observed.

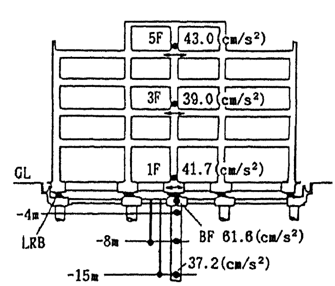

Fig.13 Max.Acceleration

Figure 14 shows the acceleration waves. And the Fourier Spectra at foundation and 1st floor are shown in Fig.15. The 1st mode frequency is 1.07(Hz) and the 2nd mode is 6.1(Hz).

The 1st mode value is plotted in Fig.9. The 2nd mode cannot be seen in 3rd floor wave.

Figure 16 shows the comparison of a recorded acceleration and a simulated one by using model-A in Fig.2. Simulated waves are almost identical with the records. From acceleration waves LRB's hysteresis loop during this earthquake was induced. Figure 17 shows the induced hysteresis loops and the simulated ones by the design loops of LRB shown in Fig.3.

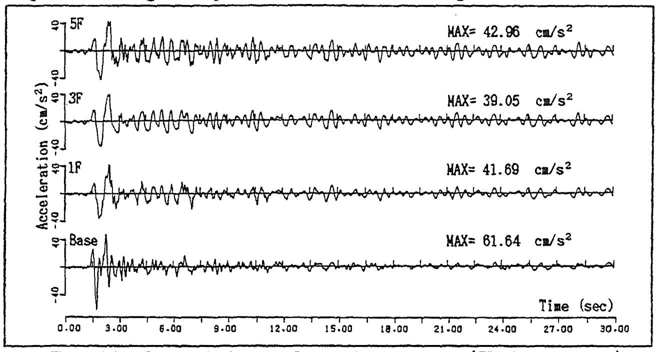

Fig.14 Recorded acceleration waves (EW-Direction)

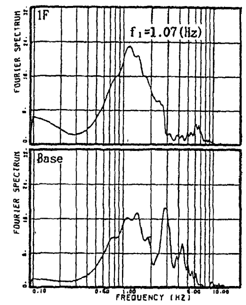

Fig.15 Fourier Spectra

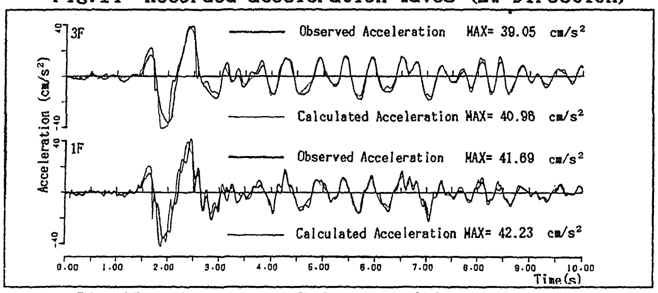

Fig.16 Accuracy of Simulated Accelerations

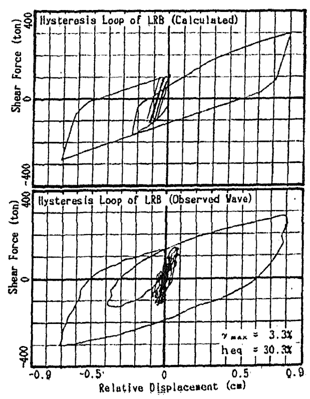

Fig.17 Hysteresis Loop

CONCLUSION

The five story base-isolated Technical Center Building was designed and constructed by using LRB. In various kinds of tests and observations, the dynamic characteristics of the building were examined. The measured values indicate the accuracy of the design.

ACKNOWLEDGEMENTS

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