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STUDY ON EARTHQUAKE RESPONSE CHARACTERISTICS OF BASE ISOLATED FULL SCALE BUILDING

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SUMMARY

This paper presents the seismic design of a base isolated full scale building, static and dynamic tests and earthquake observation on the chracteristics of the base isolation system. It is confirmed that the earthquake response accelerations are remarkably reduced compared with that of ordinary designed building.

INTRODUCTION

A full scale 5-stories reinforced concrete and Base Isolated building under the name of High Technology R&D Center (Photo.1, Fig.1) was costructed at the end of August 1986 in the Technical Research Institute of Ohbayashi Corporation at Kiyose-shi, Tokyo. The Base Isolation system (Photo.2) consists of 14 laminated natural rubber pads and 96 Steel Bar Dampers. The weight of superstructure is about 2800tons. Experimental and analytical studies have been made in order to ascertain the performances of this building.

SEISMIC RESPONSE ANALYSIS.

The following three types of input design earthquakes are employed : a) General recorded ground motions such as EL-CENTRO 1940, TAFT 1958 , b) Recorded ground motion with longer period components such as HACHINOHE 1968, and c) Artificial ground motions considering soil characteristics of construction site.
The intensity of input design earthquakes are 25 kines for primary design and 50 kines for secondary design . The design criteria for 50 kines are as followes :
The maximum response of story shear forces for superstructure is less than the yielding shear force and the maximum displacement of base isoiation devices is less than 25cm with safety factor of 1.5. The base isolation devices has a small stiffness in horizontal direction and a large in vertical direction. Fig.2 shows the response shear force coefficients as well as the maximum response of relative story drift for 25 kines input ground motion in the design. According to these figures, the superstructure has almost no relative displacement between stories.
As the results , design base shear force coefficient can be reduced by 25% comparing with that of conventional buildings based on Japanese Design Cord.

STATIC TEST OF BASE ISOLATION DEVICES

The horizontal and vertical performance tests of the base isolation device unit were carried out in prior to the construction of the building. These tests are regarding with mechanical property of stiffness, strength and damping, ultimate capacities of displacement and strength, and durability progressive creep. (Ref.1)

Here, the horizontal force-displacement curves of the rubber pads under 200 tons vertical load is shown in Fig.3(a) showing that rubber pads have linear characteristics in the range of more than 37.5cm. The horizontal force-displacement curves of special steel bar dampers (Fig.4) is shown in Fig.3(b) . The total absorbed energey of 96 steel bar dampers to be installed in the full scale building is sufficiently large in quantity against the responses for 50 kine input velocity as shown in Fig 6 . Fig.5 shows the total shear force-displacement relationships of the base isolation system.

VERIFICATION TESTS

The static and dynamic force application tests in both horizontal directions (X-EW and Y-NS) were conducted using constructed building.

Static Test Static jacks attached to the reaction frame installed on the ground side were used for force application. Approximately ±100mm enforced displacement was applied. Fig.7 shows the force-displacement relationships of Y direction with design values attached. Hysterisis loops with some slip around zero displacement is caused by the gap (±0.5mm) between the steel bar and the spherical bearing supporting the steel bar damper. Tests results are in good correspondence with design specifications with more than 10mm displacement ranges.

Dynamic Test Dynamic horizontal and torsional force were applied to the the center of the 1st.floor by using two shaking machines(2 ×3tonf). The measurement gauges are the high sensitivity accelerometers.

The results of dynamic tests are as follows: 1)First , the tests were executed for rubber pads only, removing steel bar dampers. The 1st natural period is 2.5 seconds for both X and Y directions and its damping coefficient is about 2%. This natural period of 2.5 seconds is a little shorter compared with the design period because the stiffness of Rubber Pads depends on the displacements in the smaller ranges. The torsional 1st natural period is 2.0 seconds and damping coefficient is about 3% . 2) Fig.9 shows the natural mode shapes for Y direction and Fig.10 shows the resonance curves of the building with the proper base isolation system.

These natural periods and damping coefficients are showen in Table 1.

Horizontal displacement of the rocking vibrations occupy in the roof floor displacements, caused by supporting piles and ground rigidity,and rubber pad vertical elasticity, are very small as shown in Table 2.

Analytical results Fig.8 shows the analytical model having 10 degrees of freedom considering both horizontal and rocking displacements, and also considering the nonlinear effect of the stiffness of rubber pads and steel bar dampers in the small displacement ranges , although their stiffness becomes close to the design values as the displacements becomes larger (Fig.7(c)). Analyzed mode shapes and resonance curves compared with experimental values are shown in Fig.9 and Fig.10. Table 1 shows analyzed values of the natural periods and the damping coefficients in comparison with experimental values. It is ascertained that analyzed values provide good agreement with the dynamic test values, and it can be also said the vertical rigidities of ground and rubber pads are sufficiently large (Table 2).

EARTHQUAKE OBSERVATION

The earthquake observation system (Fig.11) adopts digital recording methods which can handle 64 components observed signals through its retarding device of 20 seconds. Since completion of the building, a large number of earthquakes have been recorded (Fig.12) though they are rather small (Ref.2). Table.3 shows the dimension of representative earthquakes and the maximum acceleration records of the building and free field (GL-0.5m) .

Characteristics of Ground Motions The typical acceleration response spectrum (damping coefficient: h=5%) exicited by waves observed on the basement are shown in Fig.13. It is observed that the acceleration responses in the period ranges of 1～3 seconds are small in case of RD-15 and RD-18 earthquakes and nearly equal to the input maximum acceleration in case of RD-05, RD-40 earthquakes which have rather larger magnitudes and longer epicentral distance as shown in Table 3.

Base Isolation Effects The observed response displacements of base isolation system are small (less than 1 cm) comparing with the 3 cm yielding displacements of steel bar. Therefore, the damping effects of the steel bar dampers were not expected , but base isolation effects to reduce the acceleration response were remarkable compared with ordinary building having the periods of 0.1～0.5 seconds (Fig.13) . As for further discussions, Fig.14(a) (in the case of RD-05) and Fig.14(b) (RD-18) show the response spectrum of various damping coefficients of h=2% , 5% and 10%. It is clarified that maximum measurement accelerations(·) of the 1st mode in the case of RD05 is affected by damping coefficients, but not in the case of RD-18 in the ranges of base isolation periods. As the results, base isolation effects would be larger when subsidiary damper be attached for the small or interemediate earthquakes having rather longer periods such as RD05 .

Fig.15 shows the role of subsidiary damper and steel bar damper. Subsidiary damper of friction type, has been attached to the High Tech. R&D Center building since April 1987. Fig.14(c) shows the reduced acceleration response due to damping effects during the RD-40 earthquake, though it had larger response values in rather longer period ranges as shown in Fig.13. Fig.18(a) shows the recorded acceleration waves during RD-40 earthquake on the roof floor of High Tech. R&D Center building , the ordinary building (3 stories reinforced concrete structure : Fig.17) and free field . The base isolation effects were observed fairy well.

The acceleration at the roof of the isolated building was 1/5 of that at the free fild, and approximately 1/8 of that at the roof in the ordinary building.

The earthquake response waves can be simulated well as shown in Fig.18(b). Fig.19 also shows the observed maximum accelerations of the latest eathquake of RD-56 on the High Tech. R&D Center , to present effectiveness of base isolation compared with ordinary building.

CONCLUSIONS

In Japan there have been many structural damages in NIIGATA 1924.6 ,TOKACHI-OKI 1968.5, OHITAKEN-CHUBU 1975.4, IZU-OHSHIMA KINKAI 1978.1, MIYAGIKEN-OKI 1978.6, and NIHONKAI-CHUUBU 1983.5 earthquakes in these 30 years. The base isolated building would be useful to reduce the acceleration responses and structural damages, and therefore, the performances of rubber pads and damper devices become important to obtain the excellent base isolation effects , particularly , against the earthquake ground motions having longer periods.

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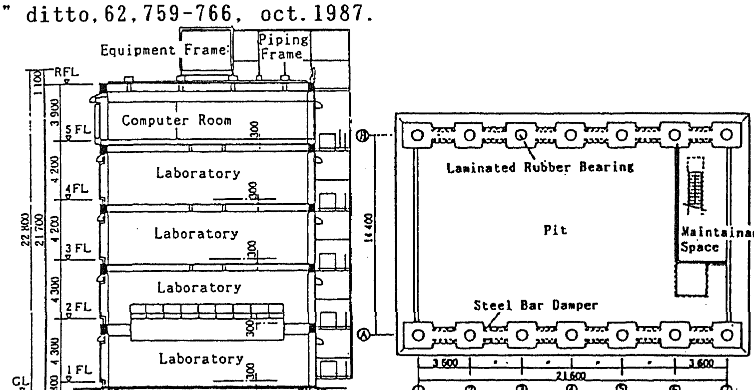
2. Takeda,T., Okada,H., Teramura,A.,Seki,M.,Nakamura,T.,Kageyama,M.,Nohata,A. "ditto, part13～16," ditto,62,759-766, oct.1987.

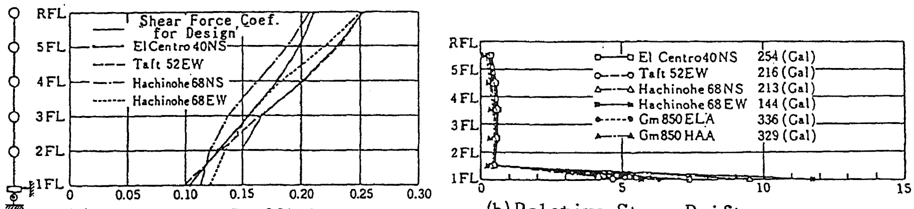
Photo 1 View of High Tech. R&D Center



(b) Basement Floor (Location of Base Isolation Devices)

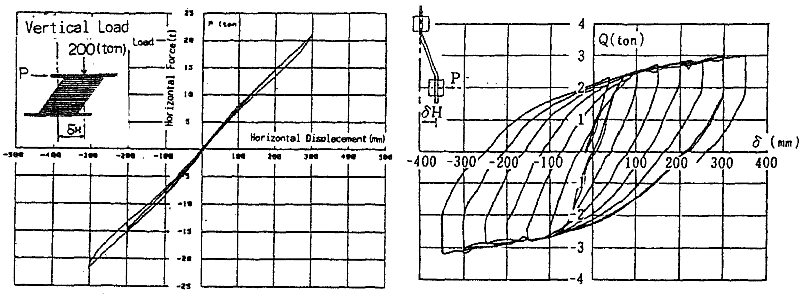
(a) Section

Fig 1 Section and Plan of High Tech. R&D Center building



(a) Shear Force Coefficient (b) Relative Story Drift

Fig 2 Response Shear Force Coefficient and Relative Story Drift (25 kine, X-direction)



(a) natural rubber pads (b) 2-29mmΦ steel bar Damper

Fig 3 Horizontal Force-Displacement Curve

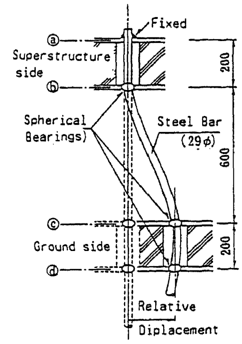


Fig 4 Mechanism of Steel Damper

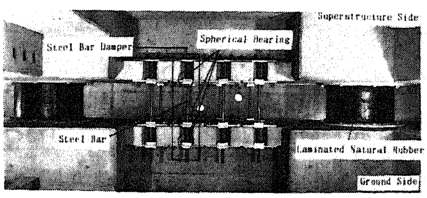


Photo 2 View of Base Isolation Devices

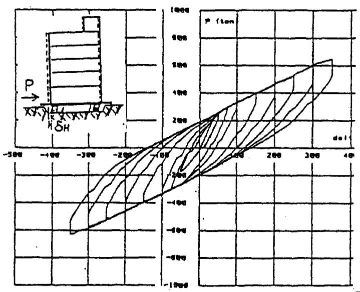


Fig 5 Horizontal Force-Displacement Curve of Total System

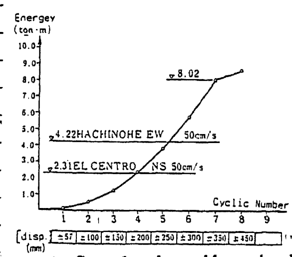
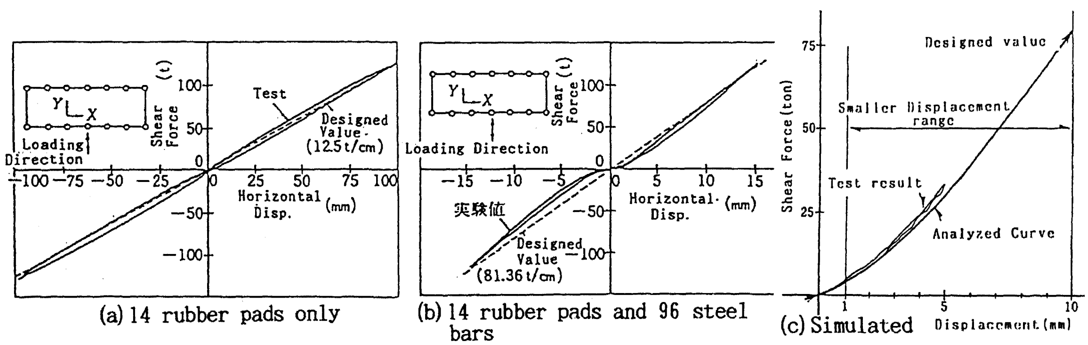


Fig 6 Cumulative Absorbed Enagey (steel bar)



(a) 14 rubber pads only (b) 14 rubber pads and 96 steel bars (c) Simulated

Fig 7 Horizontal Force-Displacement Curve (Static tests)

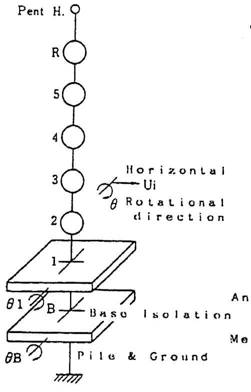


Fig 8 Analysis Model

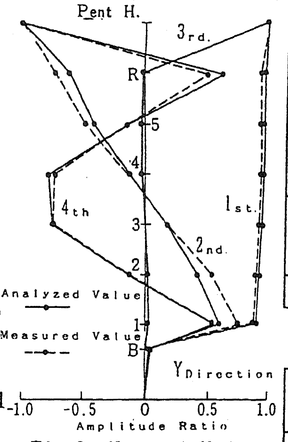


Fig 9 Natural Mode Shapes

Table 1 Natural Periods and Damping Coefficient (vibration tests and analysis)

Direction / Mode		Period (sec) Measured	Period (sec) Calculated	Damping ($h=C/C_c$.%) Measured	Damping ($h=C/C_c$.%) Calculated
Y (NS)	1	1.67～1.82	1.770	1.7 ～2.3	2.0
	2	0.20	0.196	2.0 ～3.0	3.2
	3	---	0.138	---	1.5
	4	---	0.104	---	1.8
X (EW)	1	1.82～1.96	1.840	1.7 ～2.5	2.0
	2	0.32	0.325	1.6 ～2.0	2.0
	3	---	0.194	---	3.0
	4	0.13	0.150	2.2	2.2
Torsion. 1		1.37	1.36	5.2 about	---

Table 2 Rocking and Sway components against R-FL horizontal disp. (unit:%)

Direction	1st Froor Measured	1st Froor Calculated	Basement Floor Measured	Basement Floor Calculated
Y Sway	95.0%	96.8	1.5	1.7
Y Rocking	<1.0%	0.046	<1.0	0.01
X Sway	88.0	90.4	1.5	1.6
X Rocking	<1.0	0.09	<1.0	0.007

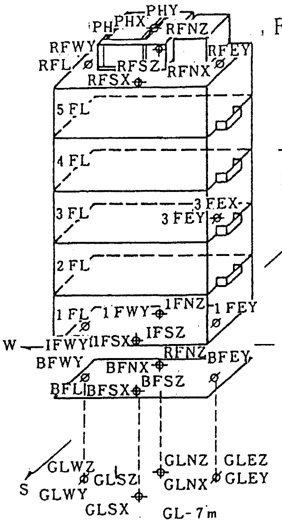
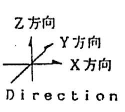


Fig 11 Observation Points of High Tech. R&D Center



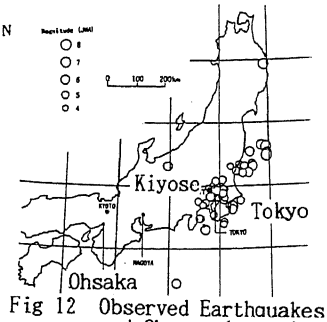


Fig 12 Observed Earthquakes and Observed station

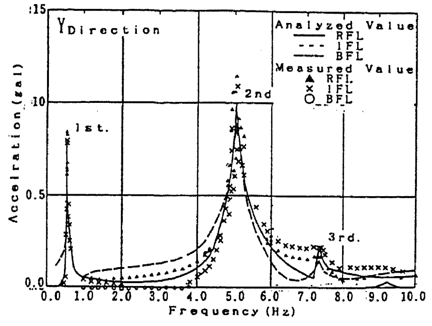


Fig 10 Resonance Curves

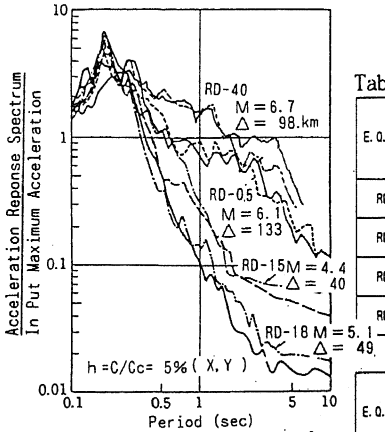


Fig 13 Characteristics of Observed Ground Motions

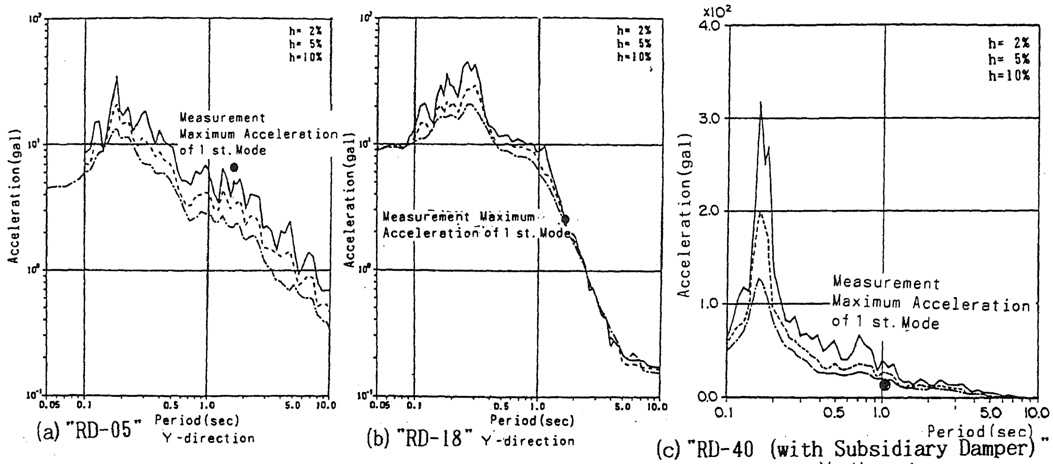
(M : magnitude,
Δ: epicenter distance, km)

Table 3 Representative Earthquake Records (without Sub Damper)

E. Q. NAME	Date	Epicentnal Position	Magnitude (JMA)	Depth (Km)	Epicentral Distance (Km)	Hypocentral Distance (Km)	Maximum Acceleration Free Field X	Free Field Y	Top of the Building X	Top of the Building Y
RD-01	1986. 9.20 12:04	Ibaragi-ken Chubu-engan	5.0	56	126.	138.	3·5	3·7	1·1	0·9
RD-05	1986. 11. 22 9:41	Izu-Ohshima kinkai	6.1	39	133.	139.	5.0	4.4	6.4	6.3
RD-15	1987. 2. 22 5:39	Saitama-Chiba kenzakai	4.4	85	40.	92.	2.5	3.7	1.0	0.9
RD-18	1987. 4. 10 19:59	Ibaragi-ken Nanseibu	5.1	57	49.	74.	12.4	13.1	2.8	2.7

(Part 2: with Subsidiary Damper)

E. Q. NAME	Date	Epicentnal Position	Magnitude (JMA)	Depth (Km)	Epicentral Distance (Km)	Hypocentral Distance (Km)	Maximum Acceleration Free Field X	Free Field Y	Top of the Building X	Top of the Building Y
RD-40	1987. 12. 17 11:08	Chiba-ken Toho-Oki	6.7	58	98.	114.	43.8	39.0	10.9	11.6
RD-56	1987. 3. 18 5:34	Tokyo-to Toubu	6.0	99	16.	100.	38.2	25.1	11.0	11.5



(a) "RD-05" Y-direction (b) "RD-18" Y-direction (c) "RD-40 (with Subsidiary Damper)" Y-direction

Fig 14 Acceleration Response Spectrum of RD-05, RD-18, RD-40 (h=2%, 5% and 10%)

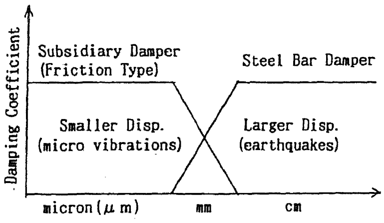


Fig 15 Role of Subsidiary Damper and Steel Bar Damper

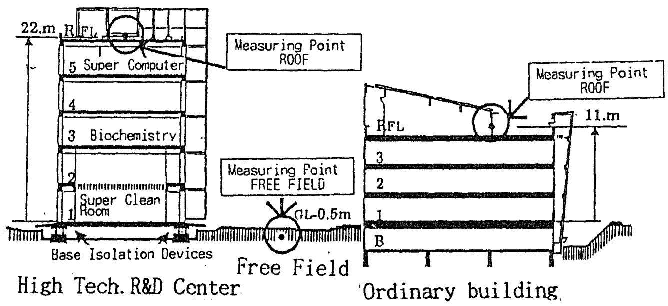


Fig 17 Observation Points of High Tech. R&D Center, Free Field and Ordinary building

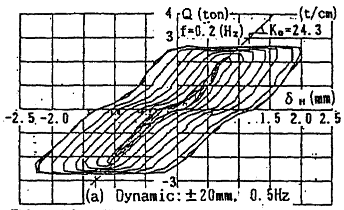


Fig 16 Horizontal Force-Displacement Curves of Friction Damper

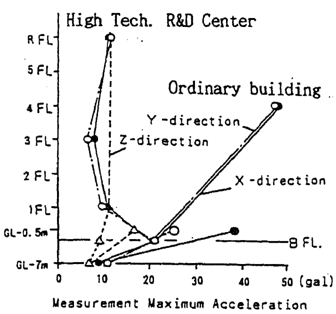
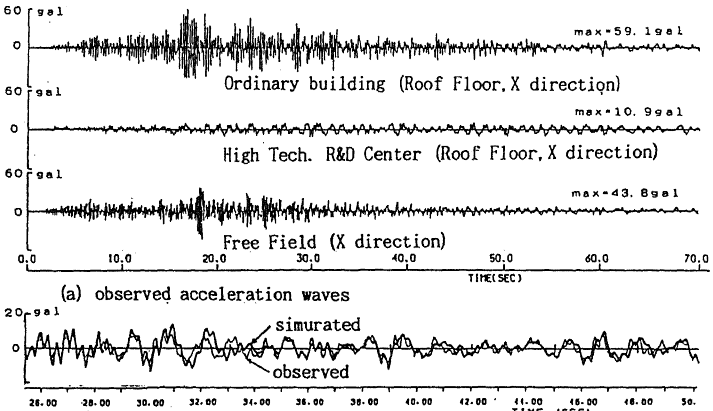


Fig 19 Maximum Acceleration of "RD-56", 1988. 3. 18



(a) observed acceleration waves

(b) observed and simurated acceleration wave of High Tech. R&D Center

Fig 18 Acceleration waves of "RD-40", Chiba-ken Toho-oki Earthquake, 1987. 12. 17