Study on Fail-Safe Mechanism in Base-Isolation Device

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1 INTRODUCTION

Recently, many kinds of base isolation systems have been developed to reduce seismic input forces, nevertheless it is important to secure the safety of a base isolated building such as nuclear power facilities even for excessively strong ground motion. As one of fail-safe devices applying to base isolation system to reduce earthquake force and secure the safety, development of a soft-landing type fail-safe (hereinafter referred to as "Soft Landing") is reported in this paper.

2 DEVELOPMENT OF SOFT LANDING

2.1 Study by Reduced Base-isolated Model

Photo.1 shows a reduced base-isolated model. The superstructure of the base-isolated model is a single-story steel-frame, having the first and roof floors of each 4 tons, then a total weight is 8 tons, and primary natural period is 0.3 second. The base isolation device is composed of 2-ton natural rubber bearings and prestressed concrete steel bar dampers (hereinafter referred to as "damper"). The period of the base isolation device is set around 1 second to approximate the natural period of comparatively soft ground at the earthquake observation site, so the model would get large vibrations in medium- and small-scale earthquakes. Base isolation elements consisting of rubber bearing, damper and Soft Landing are shown in Fig.1, while the outline of the base isolation device is shown in Fig.2. At the sliding plane of Soft Landing, Ethylene tetrafluoride resin is used to obtain favorable damping capacity and soft landing effect.

1) Basic Characteristics Tests of Base Isolation Elements
The restoring force characteristics of 2-ton rubber bearings are shown in Fig.3, and the vertical displacement accompanying horizontal deformation in Fig.4. The restoring force characteristics of rubber bearings are roughly linear until horizontal displacement of ± 3 cm, but from horizontal displacement of ± 8 cm, vertical displacement increases in the form of a quadratic curve and there is risk of the occurrence of buckling.

The restoring force characteristics when combining 2-ton rubber bearings and Soft Landings are shown in Fig.5, and the vertical displacements in Fig.6. In this case, stable restoring force characteristics are indicated up to horizontal displacement of ± 10 cm and there is no risk of buckling of rubber bearings. The damping factor increases approximately 4 to 5% and it can be seen that Soft Landing is functioning as a safety device against excessively large input. The bearing load of Soft Landing is shown in Fig.7, and it can be clearly seen how load acting on the rubber bearing is transferred smoothly to Soft Landing as horizontal displacement increases.

The horizontal-direction restoring force characteristics of this base isolation device composed of rubber bearing, damper and Soft Landing are shown put together in Fig.8. The restoring force characteristics of the base isolation device as a whole can readily be obtained from the restoring force characteristics of the individual elements. A damper is not ruptured up to horizontal deformation of ± 4 cm, with stable, spindle-shaped restoring force characteristics indicated. The damping factor of rubber bearing is approximately 3%, while with a combination of rubber bearing and damper it is approximately 15%.

Soft Landing mechanism is as follows. Due to vertical displacement of the rubber bearig as horizontal deformation increases, the building lands on Soft Landing and begins to slide, and because the weight of the building gradually shifts onto Soft Landing, frictional resistance (damping) gradually increases. Even after rupturing of the damper, Soft Landing indicates a favorable response displacement control function without applying excessive acceleration to the superstructure due to smooth transfer of load and friction, and prevents buckling due to excessive deformation of rubber bearings. Even after large deformation, there is restoration to the origin by the restoring force of the rubber bearing.

An analytical model of the restoring force characteristics of a base isolation device composed of rubber bearing, damper, and Soft Landing is shown in Fig.9. The rubber bearing was made a linear spring model, the damper a bilinear model, and Soft Landing a model where friction of a constant gradient (K_F) acts from the displacement(δ_F) at which the superstructure load begins to be transferred.

2) Shaking Table Tests

The accelerations and displacements waveforms of measurements and simulation analyses on input of the EL CENTRO 1940 wave 164 gal, to a base-isolated model of rubber bearing and Soft Landing are shown in Fig.10. The analytical results correspond well with the test results and the horizontal displacement of the rubber bearing was controled in 5.25 cm by the function of Soft Landing. Contrasted to this, in analysis of the same input to a base-isolated model of only rubber bearings, the response displacement increases more than 8.45 cm and buckling of rubber bearings may happen. The effectiveness of Soft Landing as a safety device can be ascertained by this.

2.2 Soft Landing Matching Actual 40-ton Rubber Bearing

A 40-ton natural rubber bearing is shown in Fig.11. The configuration of this rubber bearing is roughly the same as that of the kind used in actual buildings. The design load is 40 tons, the horizontal-direction frequency approximately 0.5 Hz, the vertical-direction frequency approximately 15 Hz, and allowable deformation 15 cm. A 40-ton Soft Landing is shown in Fig.12. A load cell for measuring the bearing load is set inside the Soft Landing, and a suitable damping force and soft landing effect is obtained through the use of a supermacromolecular polyethylene at the sliding plane. The coefficient of friction μ of Soft Landing is approximately 0.21, and no problem concerning durability such as abrasion of the sliding plane was seen. A dynamic loading Test System is shown in Fig.13.

1) Fundamental Characteristics Tests

The results of fundamental characteristics tests of sine wave horizontal displacement± 15 cm input at vibration frequency 0.5 Hz are described. The restoring force characteristics of a rubber bearing at axial force of 40 tons is shown in Fig.14, and the vertical displacement is shown in Fig.15.

The restoring force characteristics of the rubber bearing are roughly linear up to the allowable horizontal deformation of ± 15 cm. The damping factor of the rubber bearing is approximately 2%. The restoring force characteristics in case of combination of rubber bearing and Soft Landing are shown in Fig.16, the vertical displacement in Fig.17, and the bearing load of Soft Landing in Fig.18.

2) Limit Tests

The results of limit tests of sine wave horizontal displacement 0 to 35 cm input at vibration frequency 0.5 Hz are described.

The restoring force characteristics, vertical displacement, and the bearing load of Soft Landing in limit tests of the combination of rubber bearing and Soft Landing are shown in Figs.19, 20 and 21. In Fig.19, stable restoring force characteristics up to horizontal displacement of 35 cm (shear strain of rubber being 274%) equal to the diameter of the rubber bearing are seen, and risks of hardening and buckling of the rubber bearing are not recognizable. From Fig.21, it can be seen that the load acting on the rubber bearing is transferred smoothly to Soft Landing as horizontal displacement increases. The value of damping factor becomes larger as horizontal displacement is increased, and attains a maximum of approximately 8%.

It may be considered from limit tests that design of a more compact base isolation device with incorporation of Soft Landing is possible since the axial load of the rubber bearing is alleviated and stress is reduced by Soft Landing functions as a safety device against excessively large input.

2.3 Study of Application to Actual Building

As a preliminary study for application of Soft Landing to an actual building, an earthquake response analysis of a base isolation device consisting of a 200-ton rubber bearing and Soft Landing was performed.

The analytical model was the base-isolated model of a single lumped mass system of weight of 200 tons composed of the rubber bearing and Soft Landing shown in Fig.22. The period of the rubber bearing was made 2 second (stiffness of rubber bearing : K_G = 2.014 ton/cm, damping factor of rubber bearing : h_G = 2%), and the horizontal displacements when load begins to be transferred to Soft Landing : δ_F = 0, 5, 10 cm, and the frictional rigidity of Soft Landing : K_F = 0.25 K_G, 0.5 K_G, and 1.0 K_G were taken as parameters. The inputs were of four varieties of recorded earthquake waves of 75 Kine.

Fig.23 shows the response acceleration and response displacement of the superstructure with δ_F and K_F of Soft Landing on 75-Kine (765 gal) input of EL CENTRO NS waves.

According to the analyses, ① compared with base isolation by rubber bearing only, the response acceleration is reduced by the addition of Soft Landing. (However, some amplification of acceleration is seen according to the seismic wave.) ② Regarding response displacement, compared with base isolation by rubber bearing only, displacement was reduced for all seismic wave inputs, and the displacement control function of Soft Landing was evident. ③ With regard to setting of Soft Landing, the result obtained roughly was that there are the effects of reducing response acceleration and response displacement if the horizontal displacement δ_F until load starts to be transferred is made small, and the frictional rigidity K_F of Soft Landing is made high.

As a result of the above parametric study, the displacement control function of Soft Landing of reducing response displacement through the addition of Soft Landing to base isolation by only rubber bearing was confirmed, and it was ascertained that extreme amplification of response acceleration could not be seen.

3 CONCLUSION

From the results of tests and analyses, it was confirmed that a base isolation system with incorporation of Soft Landing has the functions of reducing earthquake force and securing safety against accidental excessive input, and the applicability of this system as a safety deivice for actual facilities was ascertained.

References

Ohhira,M.,Higaki,S.,Yasui,Y.,Teramura,A.,Okada,H.,Nakamura,T.(1989,1990). Application Study of Base Isolation System to Nuclear Fuel Facility (Part 3, Tests of Fail-safe Devices of Steel Bar Type Base Isolated Building Model), Ibid. (Part 4, Shaking Table Test and Analysis of Steel Bar Type Base Isolated Building Model), Ibid. (Part 9, Dynamic Tests of Fail-safe Devices of Soft-landing Type),Transactions of the Arcitectural Institute of Japan.

Ohhira,M.,Higaki,S.,Teramura,A.,Nakamura,T.,Kobatake,M.,Hisano,M.(1990). Earthquake Response Characteristics of Base-isolated Building Models with Fail-safe Devices. Proc. of 8th Earthquake Engineering Symposium of Japan, Vol.2, pp.1719-1724.

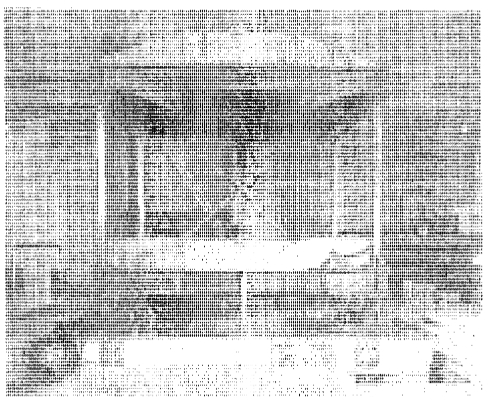
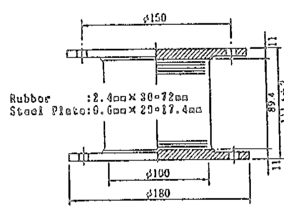
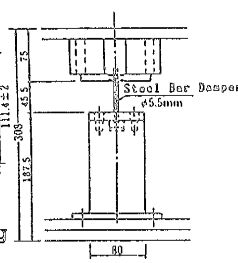


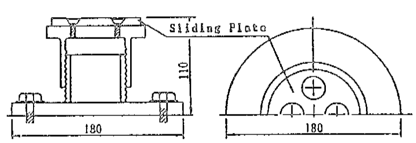
Photo.1 Reduced Base-isolated Model



2-ton Rubber Bearing

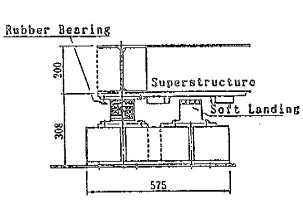


Steel Bar Damper

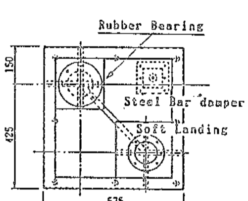


Soft Landing

Fig.1 Base Isolation Elements



(a) Elevation



(b) Plan

Fig.2 Outline of Base Isolation Device

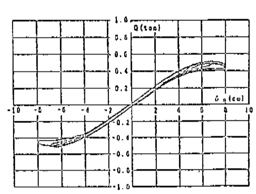


Fig.3 Hysteresis loop

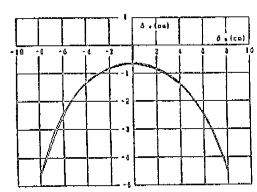


Fig.4 Vertical displacement

(2-ton Rubber Bearing)

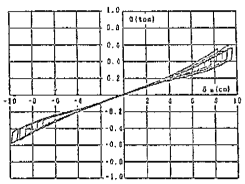


Fig.5 Hysteresis loop

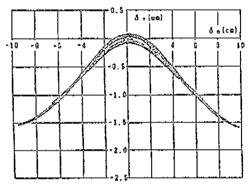


Fig.6 Vertical displacement

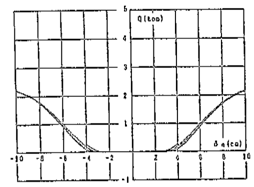


Fig.7 Landing load

(2-ton Rubber Bearing and Soft Landing)

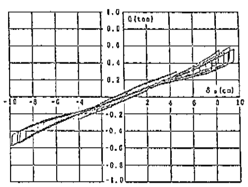


Fig.8 Hysteresis loop
(2-ton Rubber Bearing,
Damper and Soft Landing)

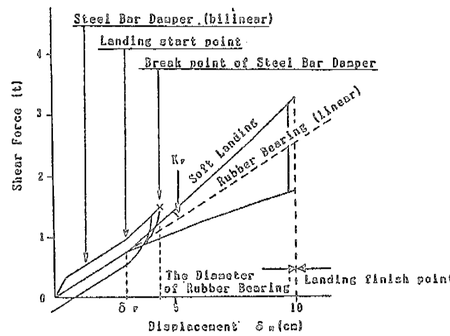
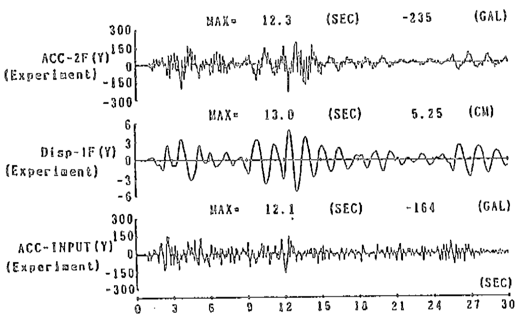
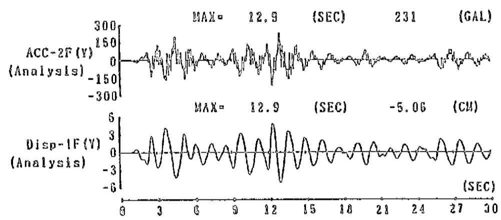


Fig.9 Hysteresis loop (Analytical Model)





(EL CENTRO 1940 Wave 160 Gal Input)

Fig.10 Comparison of waveforms of Reduced Base-isolated Model
(Rubber Bearing and Soft Landing)

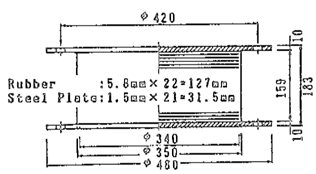


Fig.11 40-ton Rubber Bearing

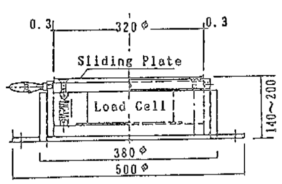


Fig.12 40-ton Soft Landing

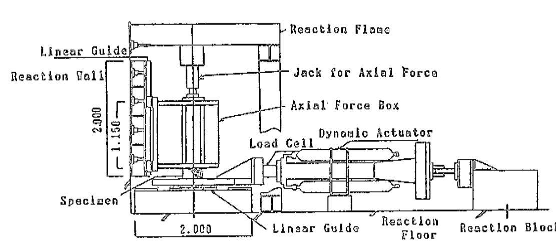


Fig.13 Dynamic Loading Test System

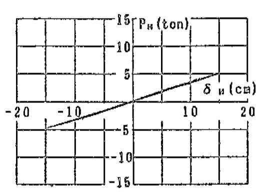


Fig.14 Hysteresis loop

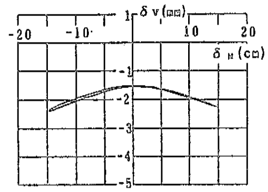


Fig.15 Vertical displacement

Fundamental Characteristics Tests (40-ton Rubber Bearing)

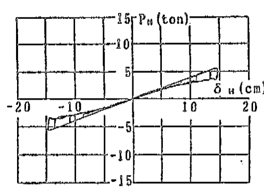


Fig.16 Hysteresis loop

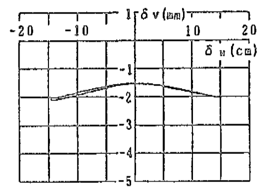


Fig.17 Vertical displacement

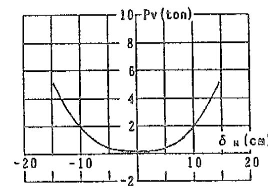


Fig.18 Landing load

Fundamental Characteristics Tests (40-ton Rubber bearing and Soft Landing)

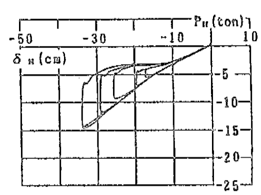


Fig.19 Hysteresis loop

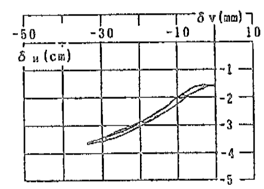


Fig.20 Vertical displacement

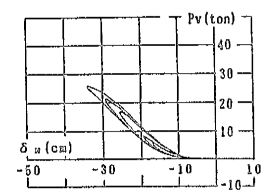


Fig.21 Landing load

Limit Tests (40-ton Rubber Bearing and Soft Landing)

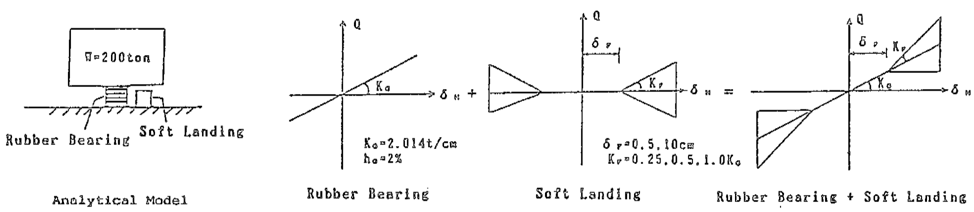


Fig.22 Analytical Model of 200-ton Base Isolation Device
(Rubber Bearing and Soft Landing)

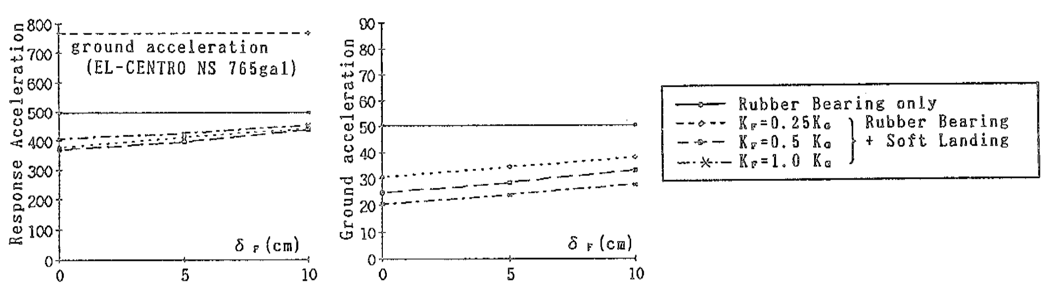


Fig.23 Responce Acceleration and Response Displacement
of EL CENTRO NS Wave 75 Kine Input (Analysis)