

COMPARISON OF SEISMIC RESPONSE OF ORDINARY AND BASE-ISOLATED STRUCTURES

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SENDAI TEST FACILITY

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INTRODUCTION

Seismic isolation is growing rapidly worldwide as a cost-effective and reliable design strategy for a wide range of critical and important facilities (e.g., hospitals, computer centers, etc.). Shimizu Corporation of Japan has a test facility at Tohoku University in Sendai, Japan. The test facility was constructed in 1986 and has two buildings: one is base isolated and the other is conventionally founded. The buildings are full-size, three-story reinforced concrete structures. The dimensions and construction of the superstructures are identical. For the past several years, Shimizu Corporation has installed a number of different isolation systems in the isolated building at the test facility to study the response of base isolation systems to actual earthquake motions.

Argonne National Laboratory (ANL) has been deeply involved in the development of seismic isolation for use in nuclear facilities for the past decade. Under the funding and direction of the U.S. Department of Energy (USDOE), ANL has been developing methodology needed to evaluate the usefulness and effectiveness of seismic isolation for advanced liquid metal-cooled reactors (LMRs). In September 1988, ANL and Shimizu Corporation reached an agreement to initiate a joint study program, utilizing existing strengths of both Shimizu and ANL to study the response of isolated structures under earthquakes. Shimizu provides their twin-building facility at Tohoku University, complete with technical staff and data acquisition systems, while ANL supplies the isolator bearings to be installed at the test facility, and performs the analysis needed for understanding the response of isolated buildings and correlating the results with observed responses. In addition, individual bearing tests are conducted by both Shimizu and ANL.

This paper compares the seismic responses of ordinary and base-isolated buildings. Earthquake records of significant importance from April 1989 to September 1991, after the installation of bearings, have been analyzed. Numerical simulations of the building responses have been performed and correlated with earthquake observation data. It is hoped that the results of this study will provide guidelines for the future use of isolator bearings for mitigation of earthquake damages.

Shimizu Corporation of Japan has two test buildings located at the Tohoku University in Sendai, Japan. The test facility consists of two buildings, full-sized three-story reinforced concrete structures, one isolated and the other conventional founded. The superstructures of the two buildings are exactly the same. The dimensions of the buildings are 6 m by 10 m. The total combined floor area of each building is 180 m². The test buildings were completed in May 1986.

A general view of the test buildings is shown in Figure 1 where the one on the right is the base-isolated building and the one on the left is the conventional founded building (unisolated). Figure 2 depicts the plan and elevation view of the buildings, in which the locations of the six (6) isolation bearings of the isolated building are also given. The test buildings were founded on a relatively hard loam layer soil whose shear wave velocity is 310 m/s. Site predominant frequency obtained through micro-tremor observation is found to be about 4 Hz. The measured fundamental frequencies of vibration and damping factors of the ordinary building are 3.63 Hz and 1.6% in the transverse direction and 4.39 Hz and 1.4% in the longitudinal direction.

The test buildings are heavily instrumented. The data acquisition system has 40 channels: 23 for horizontal accelerations, 14 for vertical accelerations, two for horizontal displacements, and one for outdoor temperature. The location of instruments is shown in Figure 3. It should be noted that instruments #H, I, J, K, and L are newly installed instruments provided by ANL through its NSF funded program. They were installed in June 1989 by Shimizu Corporation for the purpose of studying the lateral displacements, and rocking and torsional modes of vibrations of the isolated building and the effects of temperature variation on bearing height.

ISOLATOR BEARINGS

Two sets of bearings have been installed in the Sendai test facility. The first set of isolator bearings installed at the test facility (with earthquakes recorded from April 1989 to November 1990) was manufactured by Furon of the USA. The bearings were made of high damping-high shear modulus rubber compound. Each bearing has 33 layers of rubber, 4.85 mm (0.19 in.) per layer and 32 layers of steel shim plates, 1.9 mm (0.075 in.) per layer, and a (very high) shape factor of 24. The diameter and height of the bearing are 508 mm (20 in.) and 284.2 mm (11 3/16 in.), respectively. The bearing end plate has four dowel holes and is connected to the test building through four dowel pins.

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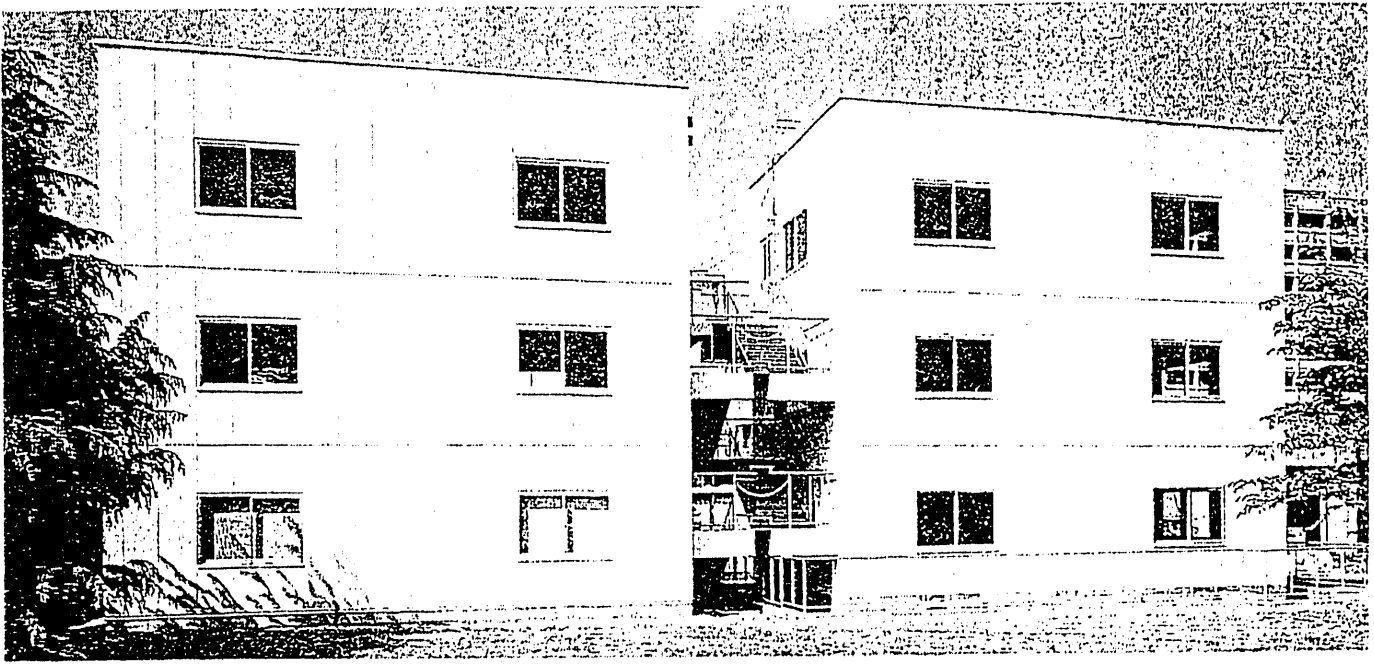


Figure 1. General View of the Test Building

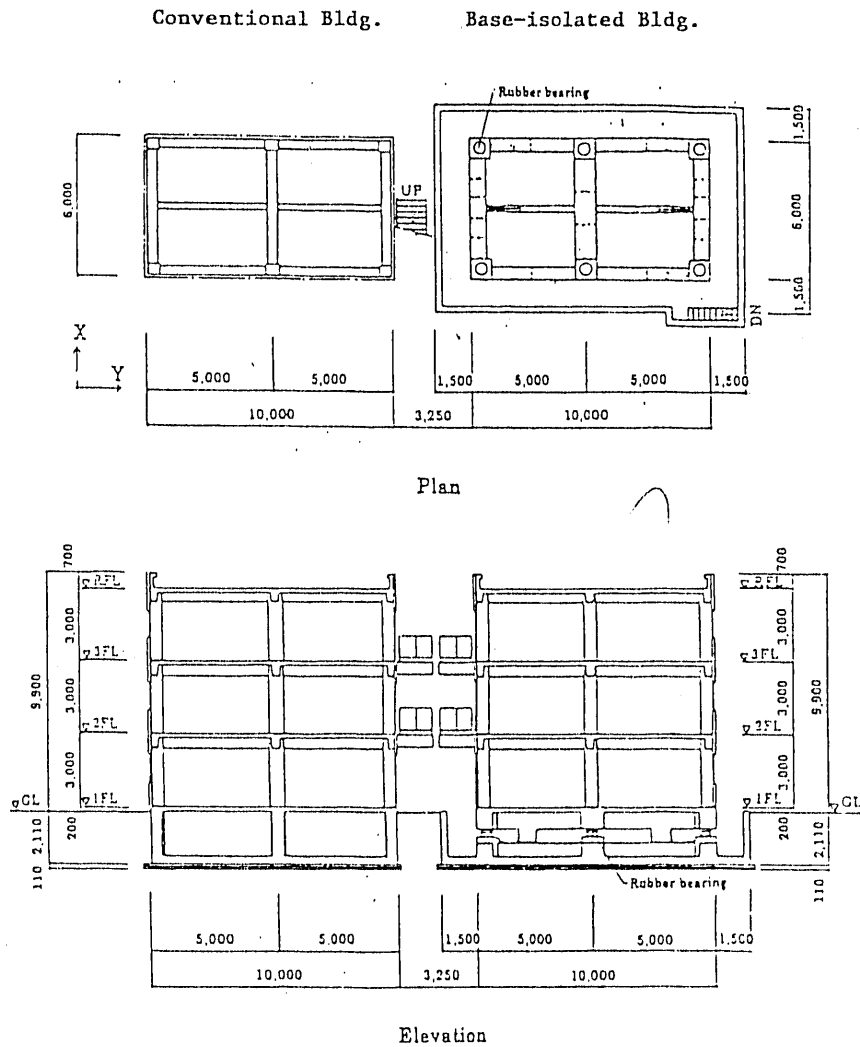


Figure 2. Plan and Elevation of the Buildings

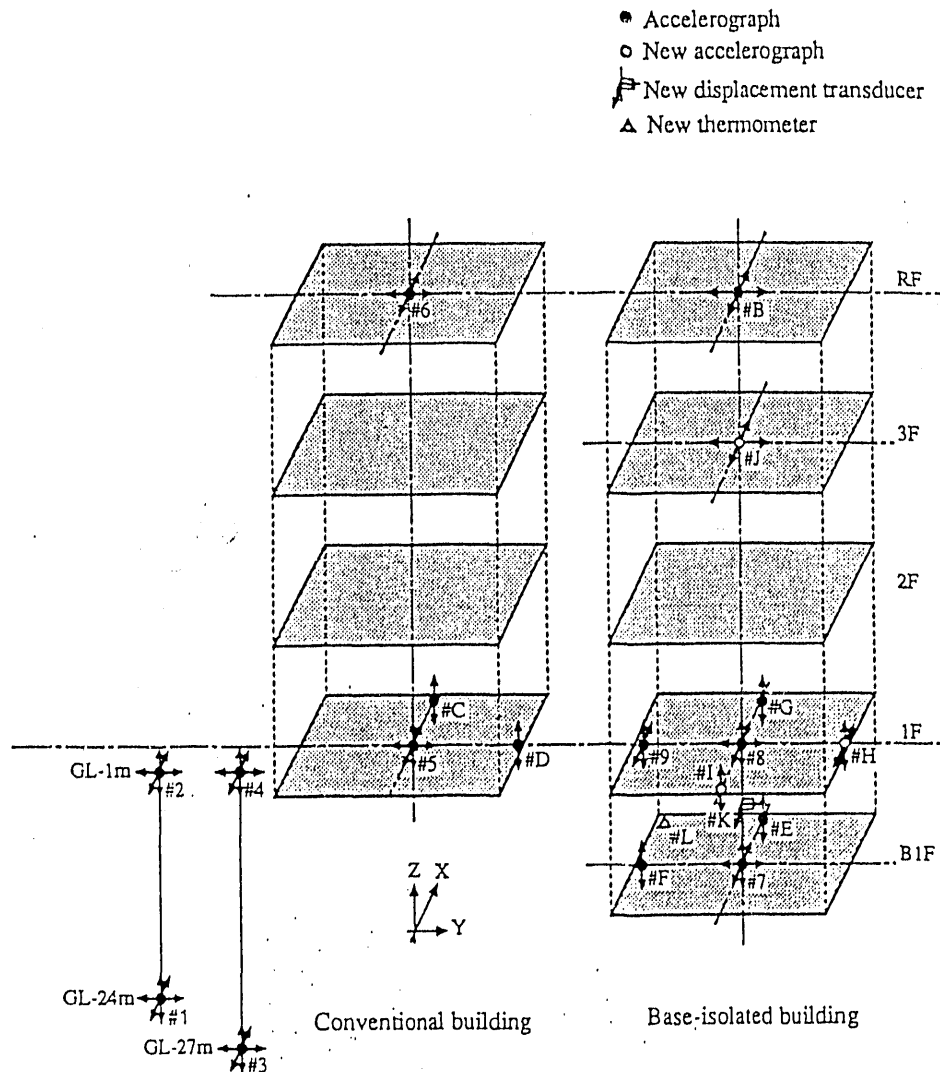


Figure 3. Location of Instruments

The second set of isolator bearings installed at the test facility (with earthquakes recorded from November 1990 to September 1991) was made by Rubber Consultants of England. The bearing was made of high damping-low shear modulus rubber compound. It has 12 layers of 10 mm (0.394 in.) thick rubber and 11 steel shim plates which are 3.25 mm (0.128 in.) thick, and a shape factor of 8.75. The shim plate diameter is 350 mm (13.78 in.) and there is 12.5 mm (0.49 in.) of cover for a total diameter of 375 mm (14.76 in.). The bearing has oversized flange plates that permit it to be bolted to the test building. The configurations of the two different bearings are compared in Figure 4.

SITE EXPERIMENTS

For the purpose of investigation of the basic properties of the test building, forced vibration tests, static loading tests, and snap-back tests were performed right after the installation of new set of bearings. The natural frequencies and dampings were determined from the forced vibration tests.

A vibration exciter was installed at the center of the roof of the isolated building and sinusoidal forces were applied horizontally to the building. Resonance curves of the base-isolated building to various levels of eccentric moment of the exciter were obtained.

EARTHQUAKE OBSERVATION

The Furon bearings were installed in April 1989 and removed in November 1990. During that period, a total of 37 earthquakes were recorded. Figure 5 shows the distribution of epicenters of recorded earthquakes. Ten earthquakes out of 37 recorded have the value of maximum acceleration on the ground surface above 3 gal.

The Rubber Consultants bearings were installed in November 1990. After installation, 17 earthquakes were recorded (from November 28 to August 8, 1991). Figure 6 shows the distribution of epicenters of recorded earthquakes. Only three earthquakes have the value of maximum acceleration on the ground surface above 3 gal.

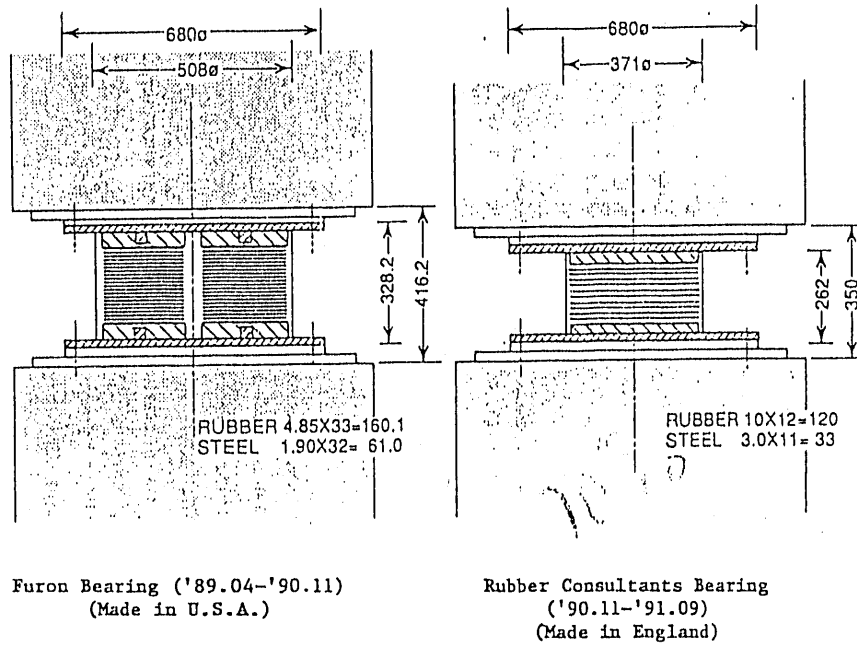


Figure 4. Configuration of Bearing

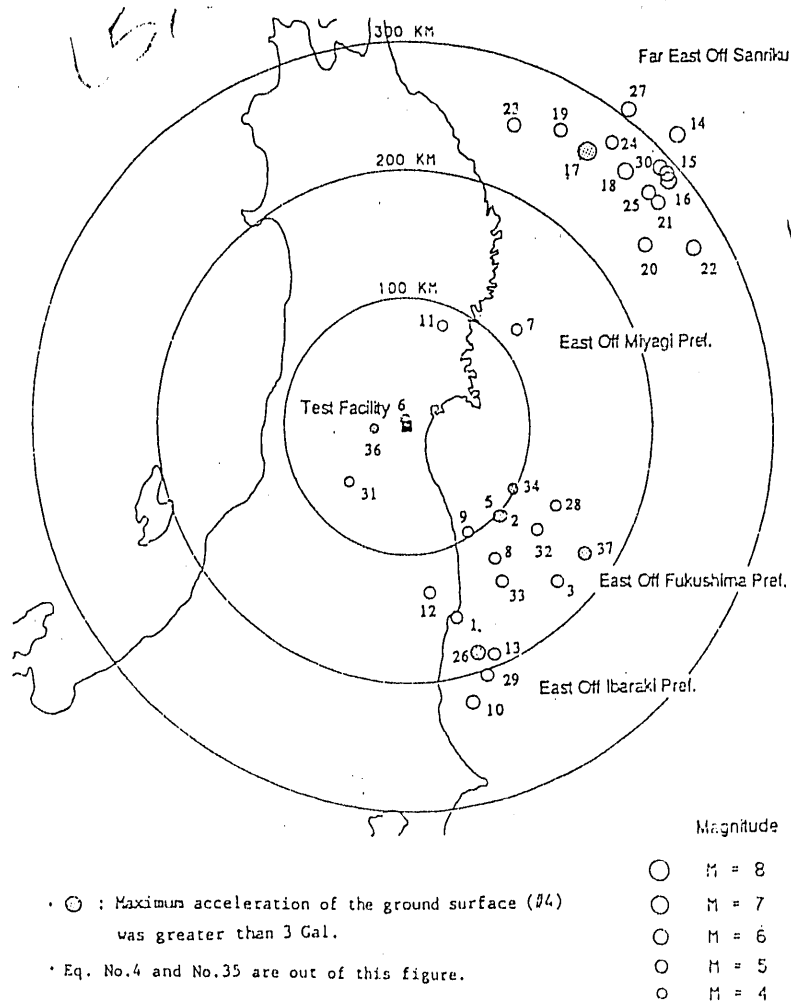


Figure 5. Distribution of Epicenters of Recorded Earthquakes #1-37

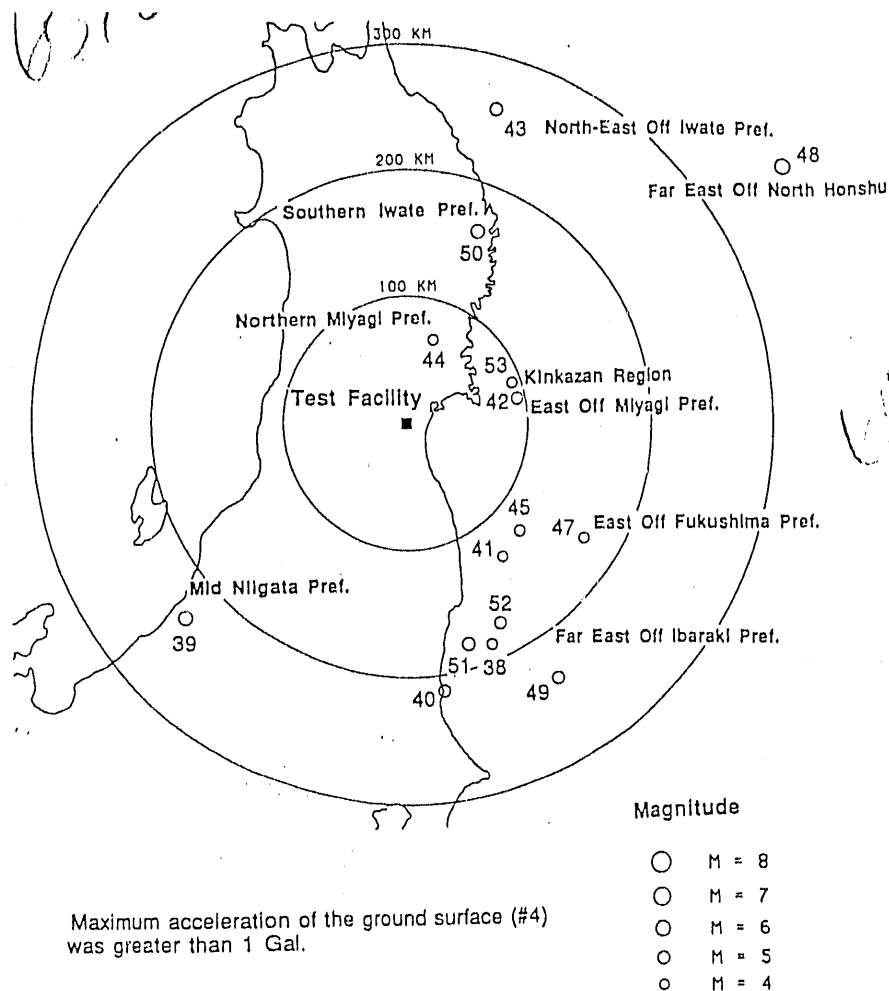


Figure 6. Distribution of Epicenters of Observed Earthquakes #38-54

NUMERICAL SIMULATION

Numerical analyses were performed with an ANL-developed computer code, SISEC [1]. Two mathematical models were used: one bilinear elastoplastic model and the other viscoelastic model. In the bilinear elastoplastic model, two elements were used to represent the isolator. One element is a linear spring element and the other is a nonlinear elastoplastic spring element. A bilinear force displacement constitutive equation was used for the nonlinear spring element. In the viscoelastic model, the material was assumed to be isotropic in its virgin, as well as in a deformed or damaged state. Volumetric and deviatoric responses were separated. Damage or degradation of the material was assumed to have occurred in the shear response. The damage mechanism has incorporated the softening behavior of rubber with increased strain deformation. The constitutive equation of the viscoelastic model uses five parameters which can be derived from the experimental data obtained through elastomer coupon or isolator bearing tests. Responses of the isolated building obtained with the bilinear and viscoelastic models have been compared with the observed data recorded at the test

building. The comparison shows that both models can predict the actual behavior of the isolated building rather accurately. Detailed results are given in Refs. 2 and 3.

COMPARISON OF BUILDING RESPONSES

The responses of the conventional and isolated buildings can be compared by studying the amplification factors of the buildings under earthquake motions. Define the amplification factor (AF) of the building as:

$$AF = \frac{\text{Maximum acceleration at instrument \#6 or \#B}}{\text{Maximum acceleration at instrument\#4}}$$

See Figure 3 for instrument locations. The amplification factors for the 37 earthquakes in the X-, Y-, and Z-directions (transverse, longitudinal, vertical) of the conventional and isolated buildings for the Furon bearings are shown in Figure 7. In the Y-direction (longitudinal), for earthquakes with ground acceleration less than 12 gal, the amplification factor of the isolated building is larger

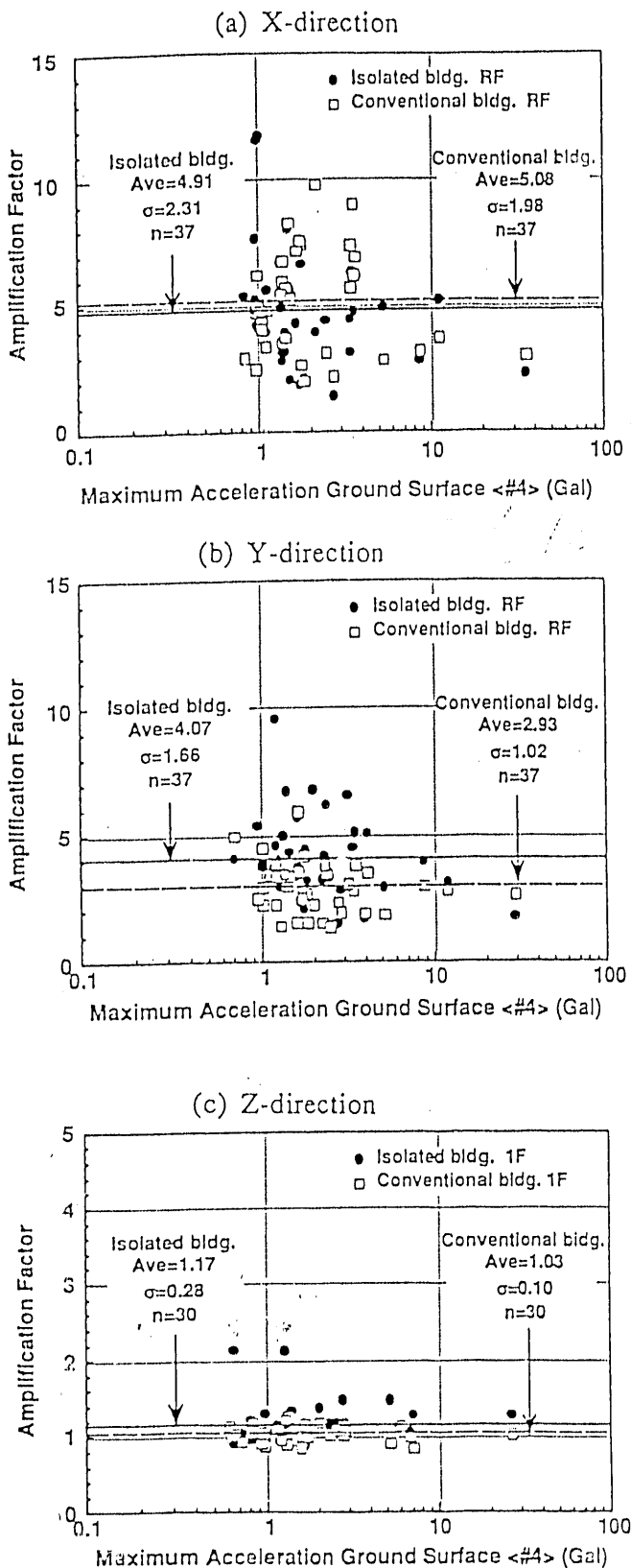


Figure 7. Amplification Factors (N=37), Furon Bearing

than the amplification factor of the conventional building. This indicates that the isolated building in the small range of earthquakes is stiffer than the conventional building even

though the isolated building is designed to have a frequency of 0.75 Hz. In the X-direction (transverse), for earthquakes with ground acceleration less than 1 gal, the amplification factor of the conventional building is lower than that of the isolated building. For earthquakes with ground acceleration greater than 30 gal, the isolated building has smaller amplification factor. For earthquakes whose ground acceleration is greater than 1 gal but less than 30 gal, the amplification factors of the isolated and conventional buildings are intermixed. No definite pattern can be seen. In the vertical direction, the amplification factor of the isolated building is about the same as that of the conventional building. This is to be expected because the isolators were designed to have a very high stiffness in the vertical direction to avoid excessive vertical vibration induced by isolators.

The mean values of the amplification factors of the conventional building in the X- and Y-directions are 5.08 and 2.93, respectively, whereas those of the base isolated building are 4.91 for the X-direction and 4.07 for the Y-direction. As can be seen, the responses of the isolated building, using the amplification factor at the roof of the building as a measurement to determine the effectiveness of base isolation, shows a wide range of variations. This is because the levels of input ground motions were very low. For the 37 recorded earthquakes, the accelerations at the ground surface ranged from 3 gal to 87.8 gal, with most events near the lower value. Since the horizontal stiffness of the isolator bearings is very high in the small shear strain range and the predominant frequencies of the input motions were near the fundamental frequency of the base isolated building, the response of the isolated building does not differ too much from that of the conventional building. Thus, no conclusions can be drawn from this study based on the observed earthquake response data for these stiff, high shape factor bearings.

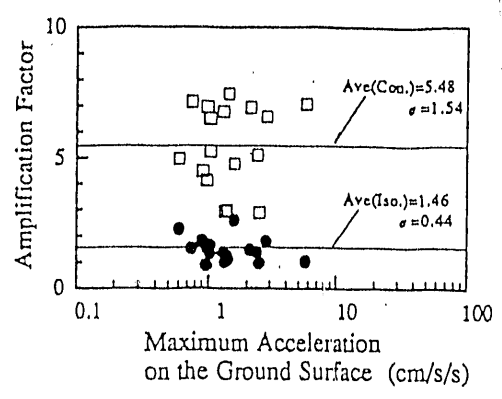
The amplification factors for the 17 earthquakes in the X-, Y-, and Z-directions (transverse, longitudinal, vertical) of the conventional and isolated buildings for the Rubber Consultants bearings are shown in Figure 8. The mean values of the amplification factors of the conventional building in the X- and Y-directions are 5.48 and 3.58, respectively. Those of the base-isolated building are 1.46 for the X-direction and 0.97 for the Y-direction. It was found that the amplification factors of the base isolated building in both the transverse and longitudinal directions are greatly reduced. They are, on average, about 1/4 of those of the conventional building.

CONCLUSIONS AND RECOMMENDATIONS

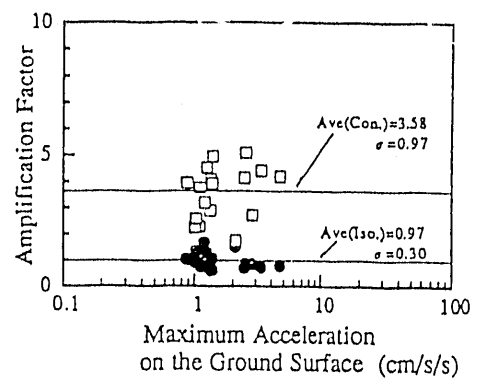
It can be concluded that isolation systems comprised of laminated steel-elastomer bearings, if properly designed, can act as effective filters to reduce seismic forces. This has been clearly demonstrated in the case of the Rubber Consultants bearings, where the measured amplification

84%

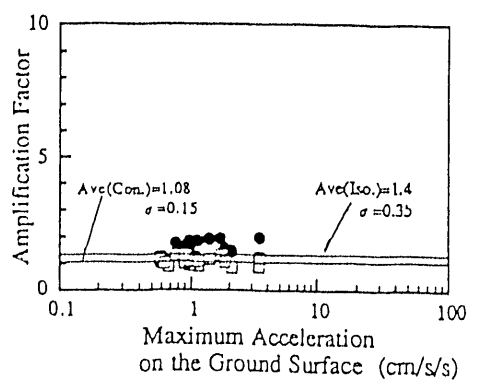
● Isolated bldg.
 □ Conventional bldg.



(a) X-direction



(b) Y-direction



(c) Z-direction

Figure 8. Amplification Factors (N=27), Rubber Consultants Bearing

factors of the isolated building in both the transverse and longitudinal directions are about 1/4 of those of the conventional building. Thus, isolation systems can be used to increase the ability of structures and their contents to withstand the damaging effects of earthquake motions. Because the shear modulus of high damping rubber varies with the level of shear strains, for small shear strains, the horizontal stiffness of the isolator bearing could be quite large. This was demonstrated in the case of the high shape factor Furon bearing. Thus, the shear strain level used in the design of isolators is extremely important to the performance of the isolated building under earthquake motions. It is recommended that the isolated building be designed for three levels of earthquake input motions. For example, $V_{max} = 25$ cm/s should be used for design earthquake input motion; $V = 50$ cm/s for unlikely occurrence of earthquake motion; and $V = 75$ cm/s for extremely unlikely earthquake motion. It is further suggested that for the design earthquake the shear strain of the bearing should be around 100%, for unlikely occurrence of earthquake, the shear strain 200%, for extremely unlikely earthquake, the shear strain 300%. In this way the isolator bearings will not be too stiff under smaller, more likely earthquakes.

The results of this joint study on full-size building tests for base seismic isolation should give the designer confidence that base isolator bearings can be designed and manufactured with more than adequate safety margins. Their performance in an isolated structure in moderate and strong earthquakes will assure that response of the isolated structure be far superior to that of the conventional structures. More importantly, the isolation system will provide high levels of damage control to the structure and will provide high levels of protection to internal equipment and other building contents.

REFERENCES

1. Wang, C. Y., Tang, Y., Uras, R. A., Marchertas, A. H., and Chang, Y. W., "Seismic Response Analysis of Base Isolated Structures with High Damping Elastomeric Bearings." Paper presented at the 1991 ASME Pressure Vessels and Piping Conference, Seismic Engineering-1991 Session, PVP-Vol. 220, San. Diego, CA, June 23-27, 1991.
2. Wang, C. Y and Gvildys, J., "Comparison of SISEC Code Simulation with Earthquake Data of Ordinary and Base-Isolated Buildings," Argonne National Laboratory report ANL/Shimizu ANL-001, August 1990.
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