Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 79 (1998)

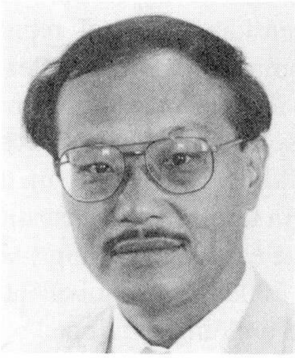
Artikel: Deformation behaviour of base-isolated buildings in near-fault earthquake

Autor: Nakashima, Masayoshi

DOI: https://doi.org/10.5169/seals-59958

Deformation Behaviour of Base-Isolated Buildings in Near-Fault Earthquake

Masayoshi NAKASHIMA
Assoc. Prof.
Kyoto Univ.
Kyoto, Japan



Masayoshi Nakaashima received his B.S. and M.S. from Kyoto Univ., Japan and Pd.D. from Lehigh Univ., USA. He has been involved with analysis and seismic design of steel buildings structures and development of experimental techniques for earthquake response simulation.

Summary

Response behavior of base-isolated buildings subjected to near-fault earthquakes was examined. Recorded, synthesized, and simplified ground motions were used in the analysis. It was found that (1) a large ground motion component appearing at a particular time tends to control the maximum deformation and (2) dynamic amplification and increase in ductility demand is most significant when the natural period of buildings under smaller vibration is 0.4 to 0.8 times the period of a large ground motion component.

1. Introduction

The 1995 Hyogoken-Nanbu (Kobe) Earthquake revealed much damage to modern building structures [1]. Although many of those damaged escaped from collapse, their functionality was severely impaired, resulting in significant loss in capital. Since that experience, importance on the control of functionality (in addition to collapse prevention) has been emphasized greatly. One solution toward this end is considered as "base-isolation." Japan has a history of construction of base-isolated buildings for nearly fifteen years [2], but the construction was limited, remaining about a dozen new base-isolated buildings annually. After the Kobe Earthquake, the construction has grown significantly, and more than 150 new base-isolated buildings were built for a single year of 1997 [3]. On the other hand, ground motion specialists address the possibility of a very large pulse-like ground motion in near-fault regions, particularly in the direction perpendicular to the fault [4,5] and warn that such large ground motion can induce very large deformations to structures with long natural periods such as base-isolated buildings. On one hand, construction of base-isolated buildings has grown with the belief that they are effective in damage control against large earthquakes; on the other hand, base-isolation may be useless for near-fault earthquakes; this rather conflicting argument has to be resolved. To provide some information on this issue, numerical response analysis was carried out for base-isolated buildings represented as SDOF systems, with the type of ground motion, type of hysteretic behavior, and natural period as major variables, and their effects on the response were examined. To understand the basic behavior of base-isolated buildings subjected to near-fault earthquakes, the ground motion was simplified as a one-cycle sinusoidal ground motion (acceleration), and the response of SDOF systems subjected to the motion was investigated in terms of the dynamic amplification of maximum deformations.

2. Numerical Analysis

In base-isolated buildings, it is a common practice to make the base-isolation devices much more flexible (in the horizontal direction) than the super-structure, and the super-structure would not go beyond its elastic limit. Therefore, an SDOF representation (Fig.1) is reasonable, with the super-structure assumed to be completely rigid and flexibility provided only by the base-isolation devices. Thirty eight base-isolated buildings previously designed were surveyed for the hysteretic behavior of their base-isolation devices. (Necessary information was obtained from the data presented in [3].) In all buildings, the maximum deformation under ambient and small vibrations was limited to 5 to 10% in terms of the shear strain (γ) of the rubber bearings, and the maximum deformation under large earthquakes (approximately 0.5 m/s in the maximum ground velocity) was limited to γ= 150 - 200%. The equivalent natural period (estimated based upon the secant stiffness) of base-isolated buildings equipped with rubber bearings with lead dampers (14 buildings surveyed) ranged from 1.2 to 1.8 sec for a deformation corresponding to γ = 15 - 20%, and the tangential stiffness under large deformations (corresponding to γ = 100 - 300%) was about 10 to 15 % of the secant stiffness at γ = 15 - 20%. The equivalent natural period of base-isolated buildings equipped with high damping rubber bearings (14 buildings surveyed) ranged from 1.1 to 1.7 sec for a deformation corresponding to γ = 20 %, and the tangential stiffness under large deformations was about 20 - 25 % of the secant stiffness at γ = 20%. The equivalent natural period of base-isolated buildings equipped with a combination of natural rubber bearings and lead and steel dampers (10 buildings surveyed) ranged from 1.7 to 1.9 sec for a deformation corresponding to γ = 10 % (at which steel dampers were expected to yield), and the tangential stiffness for large deformations was about 15 - 20% of the secant stiffness at γ = 10%. From these observations, the hysteresis of base isolation devices can reasonably be approximated to be bilinear (Fig.1), with the first stiffness corresponding to the equivalent natural period of 1.0 - 2.0 sec and the second stiffness equal to 10 - 25 % of the first stiffness. Considering these values, bilinear SDOF systems having the elastic natural period

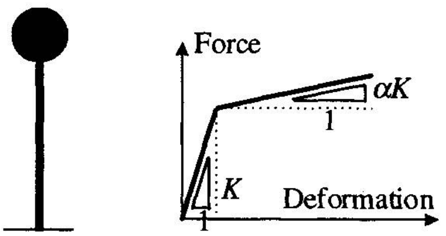
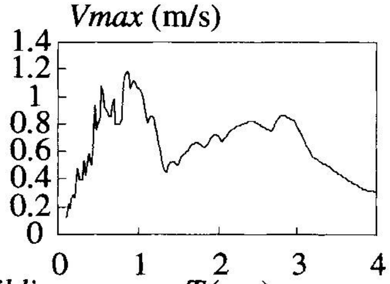
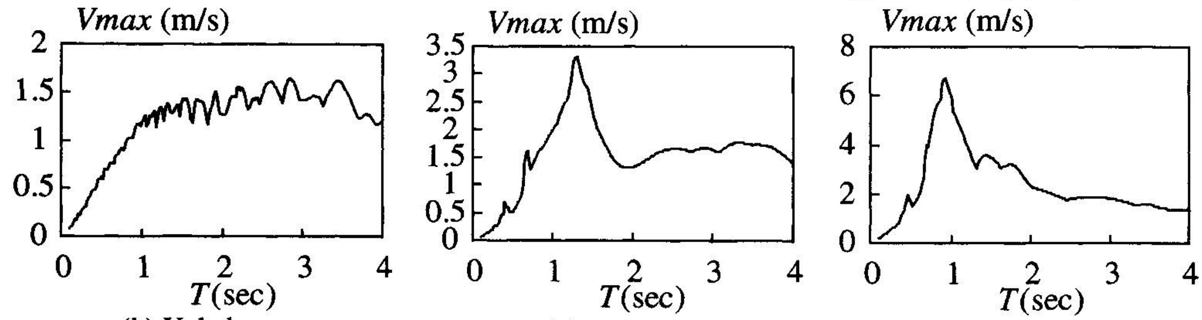


Fig.1 SDOF and bilinear representation of base-isolated building



(a) El Centro (1940)

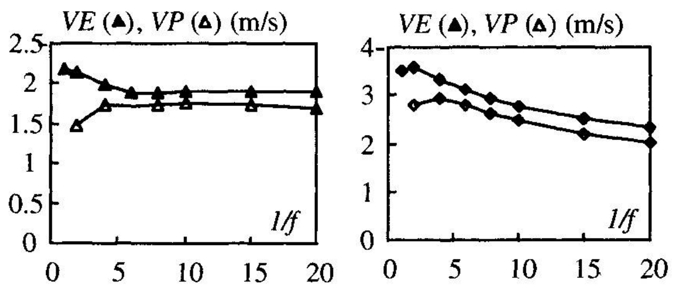


(b) Yokohama (c) NTT (1995) (d) Point-B

Fig.2 Elastic pseudo velocity spectra of ground motions analyzed

(T) of 1.0, 1.5 and 2.0 sec and the second stiffness that is 15 and 25 % of the initial stiffness were analyzed. The following four ground motions were selected: El Centro NS (1940), Yokohama (1995), NTT (1995), and Point-B(1996). El Centro record was selected as the basis of comparison because the record has been used extensively for earthquake response investigations. Yokohama (1995) is a synthesized motion having almost a constant pseudo ground velocity over a large range, developed for the simulation of ocean-ridge earthquakes. NTT (1995) is a ground motion recorded during the Kobe Earthquake, and Point-B is a synthesized motion that simulated the ground motion at downtown Kobe during the Kobe Earthquake [6] The last two motions were selected as representatives of near-fault ground motions. The elastic pseudo velocity ($Vmax$) spectra of these four motions are shown in Fig.2.

Figure 3 shows examples of input and dissipated energies in terms of the equivalent velocities (VE and VP), and Fig.4 shows the maximum deformations ($Dmax$), ratios of the maximum plastic deformation relative to the cumulative plastic deformation [$(\mu - 1)/\eta$], and the number of inelastic excursions (N). These figures are for the second stiffness equal to 25 % of the initial stiffness. In the figure, f indicates the yield force, defined as the yield force relative to the maximum force exerted if the system would respond only elastically under the same ground motion. The energy behavior is summarized as follows. In El Centro and Yokohama both input and dissipated energies are relatively constant regardless of the yield force and do not change significantly for the three natural periods (1.0, 1.5, and 2.0 sec). This supports the energy constant concept advocated in [7]. In NTT and Point-B the energy terms fluctuate with respect to the yield force and are different significantly for the three natural periods. According to Fig.4(a), the maximum deformation does not change so significantly with respect to the yield force in El Centro and Yokohama, supporting the maximum deformation constant rule [8], whereas the maximum deformation in NTT and Point-B change significantly with the yield force. Figure 4(b) shows that the ratio of maximum plastic deformation to cumulative plastic deformation is largest in NTT, followed by Point-B, El Centro, and Yokohama. The larger ratio means that the energies exerted and dissipated for one large response cycle is more significant relative to the total input and dissipated energies. This suggests that the response is more dominated by a large, single shock rather than accumulated by smaller but multiple shocks. This statement is supported by Fig.4(c), in which the number of inelastic excursions is significantly smaller in NTT and Point-B. It was also observed that in NTT and Point-B the maximum deformation was achieved around the same time regardless of the yield force and natural period, indicating that the maximum deformation was induced by a large ground motion component appearing at a particular time, whereas in El Centro and Yokohama the time at attainment of the maximum deformation varied from case to case. In summary, the response behavior for near-fault earthquakes (represented by NTT and Point-B) is characterized as follows. (1) The maximum deformation tends to be induced by a large ground motion



(a) El Centro (1940) (b) Point-B

Fig.3 Input and dissipated energies of SDOF bilinear systems (T=1.5 sec)

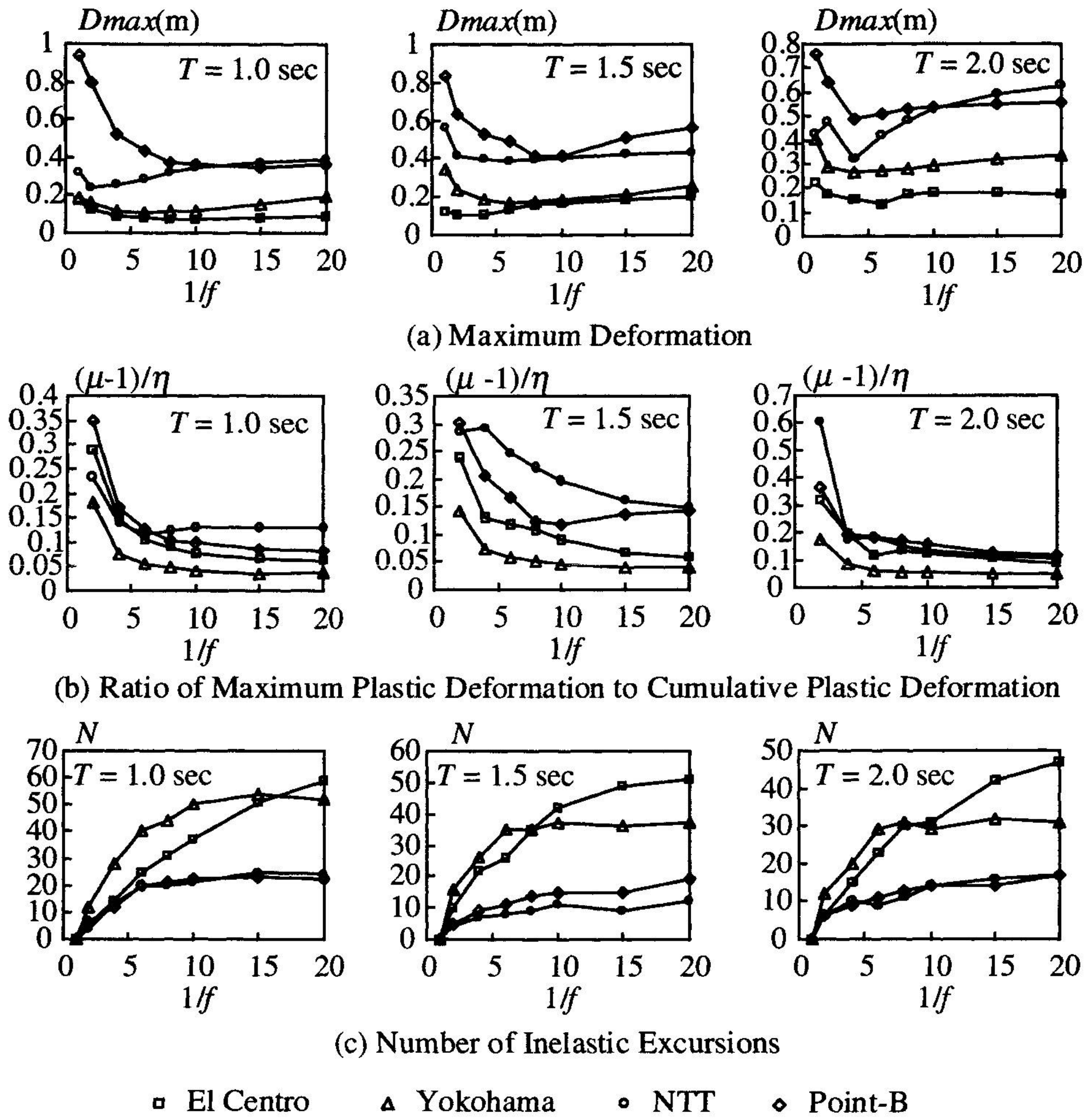


Fig.4 Response characteristics of bilinear SDOF systems

component appearing at a particular time, (2) the input and dissipated energies vary significantly with respect to the yield force and natural period, leading the energy constant concept less certain, and (3) the maximum deformation is dependent much on the yield force, making the constant maximum deformation rule less applicable.

3. Behavior of SDOF Systems Subjected to One-Cycle Sinusoidal Motion

In reference to the above discussion, it is interesting to examine how the system would behave under a large ground motion component. As a most simplified form of such motion, one cycle sinusoidal ground motion was considered (Fig.5), and the response of bilinear SDOF systems subjected to the motion was obtained.. Figure 6 shows the maximum deformation in terms of the ductility ratio (μ), defined as the maximum deformation relative to the elastic limit rotation, for various natural periods (T/Te) and the yield force (f). Here, Te is the period of the sinusoidal ground motion, and the yield force f is defined as the yield force relative to the maximum force exerted for the equivalent elastic system subjected to one-half cycle sinusoidal motion. Figure

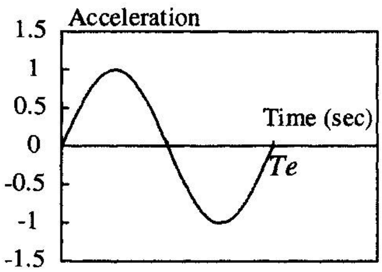
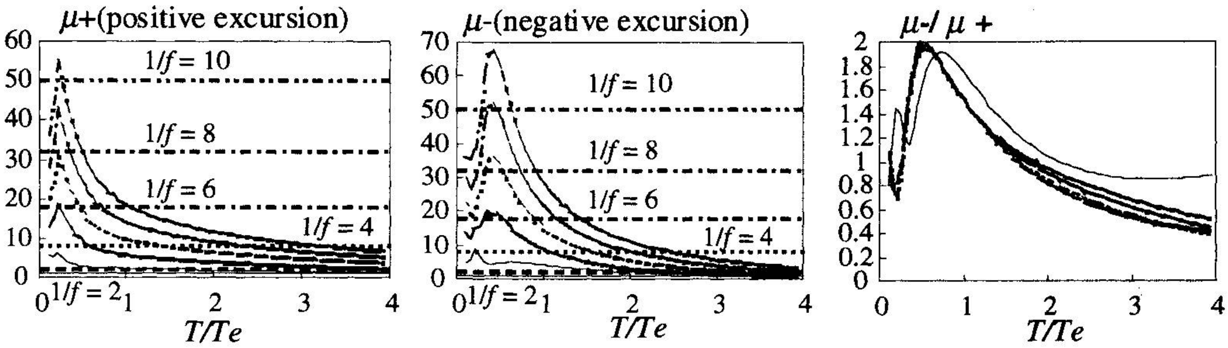


Fig.5 One-cycle sinusoidal ground motion analyzed



(a) ductility ratio for positive excursion

(b) ductility ratio for negative excursion

(c) Ratio of positive to negative ductility ratio

Fig.6 Response characteristics of bilinear SDOF systems subjected to one-cycle sinusoidal ground motion

6(a) is the maximum deformation obtained for the positive excursion, Fig.6(b) the maximum deformation for the negative excursion, and Fig. 6(c) is the ratio of the negative maximum to the positive maximum, indicating that the maximum deformation is achieved in the negative excursion for $T/Te \leq 2.0$. Most notable is that the ductility ratio is largest around $T/Te = 0.4$ and significantly reduces with the increase of T/Te. In reference to the definition of f, this figure provides an answer to the following question; i.e. if the yield force is reduced to f times the maximum force exerted in the elastic system, how much ductility should we consider? Figure 6 also shows the ductility ratios estimated based on the energy equivalent rule [8]. The obtained ductility ratios are much larger than those estimated for about $T/Te = 0.4$. Figure 7 shows another form of ductility ratio, this time the maximum deformation is normalized by the maximum deformation if the system receives the motion statically, thus enabling the direct comparison of maximum deformation. When $T/Te \leq 1.0$, the difference is significant with respect to the yield force, indicating that the maximum deformation rule is less reliable. These observations reveals that dynamic amplification and increase in ductility demand is very large for $T/Te = 0.4$ - 0.8. Earlier discussion demonstrated that the equivalent natural period of previously designed base-isolated buildings ranged from 1.0 to 2.0 sec for small deformations, which means that if a near-fault ground motion contains a large component having a period of 1.25 (= 1/0.8) sec or more, base-isolated buildings would sustain very large dynamic amplification.

A separate study is underway to derive approximate closed-form equations for estimating the ductility ratio (μ) of bilinear SDOF systems subjected to one cycle sinusoidal ground motion. The equations are applicable for $0.5 \leq T/Te \leq 2.0$, the range of most importance in terms of dynamic amplification and increase in ductility. In formulating the equations, the deformation shape was assumed to be sinusoidal, and the energy balance between the input and absorbed

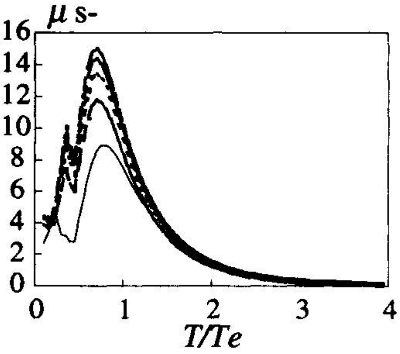
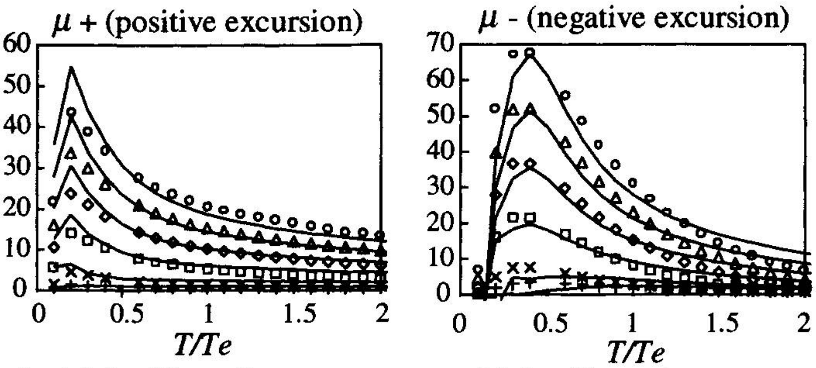


Fig.7 Ductility ratios with respect to static deformation



(a) ductility ratio for positive excursion

(b) ductility ratio for negative excursion

Fig.8 Comparison between estimated and analyzed ductility ratios

energies was considered [9]. Figure 8 shows comparison between the estimated and numerically ductility ratios, demonstrating reasonable agreement between the two.

4. Conclusion

Response behavior of base-isolated buildings subjected to near-fault earthquakes was examined. The behavior was found to be characterized such that: (1) a large ground motion component appearing at a particular time tends to control the maximum deformation and (2) energy constant concept, energy equivalent rule, and maximum deformation constant rule are less applicable. Response behavior when subjected to one-cycle sinusoidal ground motion was examined. Dynamic amplification and increase in ductility demand was found to be most significant when the equivalent natural period of buildings in small vibrations is 0.4 to 0.8 times the period of the motion.

References

[1] The Architectural Institute of Japan (AIJ) (1995). English Edition of Preliminary Reconnaissance Report of the 1995 Hyogoken-Nanbu Earthquake, 215pp.

[2] Menshin (1996). Japan Society of Seismic Isolation, No.16, pp.20-31.

[3] Building Letters (1996). The Building Center of Japan, No.348 to 359.

[4] Hall, J., et al. (1995). Near-source ground motion and its effects on flexible buildings, Earthquake Spectra, Vol.11, pp.569-605.

[5] Heaton, T. H., et al. (1995). Response of high-rise and base-isolated buildings to a hypothetical Mw 7.0 blind thrust earthquake, Science, Vol.267, pp.206-211

[6] Hayashi, Y. and Kawase. H. (1996). Strong motion evaluation in Chuo Ward, Kobe, during the Hyogoken-Nanbu Earthquake of 1995, Journal of Structural and Construction Engineering, the Architectural Institute of Japan, No.481, pp.37-46 (in Japanese).

[7] Akiyama, H. (1985). Earthquake-resistant Limit-State Design of Buildings, University of Tokyo Press, Tokyo.

[8] Newmark N. M. and Hall, W. J. (1975). Earthquake Spectra and Design, Earthquake Engineering Research Institute.

[9] Nakashima, M. (1998). Prediction of Maximum Deformation of Base-Isolated buildings subjected to pulse-like ground motions, Report to Grant-in-Aid for Scientific Research on Mitigation of Urban Disasters by Near-Field Earthquakes, Ministry of Education, Japan, 87pp.