DYNAMIC RESPONSE OF NONSTRUCTURAL SYSTEMS MOUNTED ON FLOORS OF BUILDINGS

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SUMMARY

This paper presents the results of investigation on the maximum acceleration amplification of non-structural systems mounted on floors of buildings through some experimental works using shaking table instrument. Two categories of nonstructural systems considered in this experiments are the building equipment and the building contents respectively, which are sensitive to the acceleration response of a main structure. Four recorded strong earthquake ground motions were used to examine the acceleration response of the building equipment and building contents with several type of connection to the floor surface. The analytical works were also carried out to ensure the experimental results. It is found that a light damped building equipment fixedly connected to the floor surface resulted in the largest acceleration response, while a heavy damped building contents freely laid on the floor resulted in the lower response but also produced large residual displacement. The building equipment and building contents equipped with the isolation system or those mounted on floors of an isolated main structure resulted in very low acceleration responses. Finally the experimental results are compared with two design codes of 1997 UBC and 1997 BCJ respectively. It is clarified that the nonstructural systems having low damping factor produced the acceleration responses which exceed the design codes stipulations. The acceleration generated on the isolated nonstructural systems or those mounted on floors of an isolated main structures , as being expected, satisfy the codes perfectly even though in relatively small damping.

INTRODUCTION

In several strong earthquake disasters the failure of nonstructural systems is still a big problem which cause a lot of economic losses and even generate some potential hazards that can threat the human life [Sabol 1989] [Soong, 1995]. To respond this, nowadays Japan and USA prepare a new design code which contains the consideration of performance-based design that will be effectively introduced since 2000 year. In this new procedure not only a main structure itself but also the internal nonstructural systems might be designed to show a satisfactory performance under the strong earthquake vibration [Hamburger, 1996]. Considering the performance based design this paper will show that nonstructural systems mounted on floors of a very strong structure which has a good performance under the major earthquake may be subjected to severe damage due to the large acceleration response. In strong and stiff structures the essential structural damage may not occur, the story drifts are relatively small and may not cause damage on the nonstructural systems, however damage of nonstructural systems due to large acceleration response may become serious problem [Lin and Mahin, 1985]. In this case the damping factor of a main structure and nonstructural systems play a very dominant role. In case that sufficient

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damping can not be achieved the use of base isolation device to protect a main structure or nonstructural systems could be the best solution.

The nonstructural systems discussed in this paper are limited on the building equipment and building contents which have sensitivity to the acceleration response of the building floors. Included in this categories are such as generators, water tank, chiller, vessels, etc. (kinds of the building equipment) or shelves, filing cabinets, main computers, panel boards, furniture, etc.(kinds of the building contents). The experimental works were conducted to investigate the amplification of acceleration which may occur on the building equipment (represented by low damped frame model) and the building contents (represented by actual filing cabinet). Regarding the connection type to the main structure, the building equipment is considered to be fixed to the floor to assure the function of it while the building contents can be fixedly connected, freely laid and supported on an isolation system respectively. The experimental works also observed the acceleration amplification of the equipment mounted on floor of an isolated main structure. The isolation device used in the experiment was a suspended pendulum isolation (SPI) systems which is the new device of the base isolation systems being studied and developed in the recently [Bakhshi et.al.,1998].

BRIEF DESCRIPTION OF THE EXPERIMENTAL WORKS AND TESTING OBJECTS

The first stage experiments were conducted using the model test of a 3DOF main structure, SPI and nonstructural systems respectively which dynamic characteristics are listed in table 1. The nonstructural systems modeled here represented the building equipment having low damping factor. The models of main structure and SPI represented their prototype having natural periods of 0.45 sec and 2.0 sec respectively. General layout of the experimental work using SPI is presented in figure 1. The coupled main structure and nonstructural systems were subjected to recorded earthquake ground motions which durations were compressed down using the scale factor of 2/5. This is a ratio between the natural period of SPI model to the natural period of its prototype.

TABLE 1: THE DYNAMIC CHARACTERISTICS OF THE MODELS

Model	Damping Ratio (%)	Natural Period (sec)	Remarks
SPI system	7.1	0.780	-
Main structure	0.5	0.188	1st mode
		0.061	2nd mode
		0.043	3rd mode
Non-struct. Systems	0.2	-	average

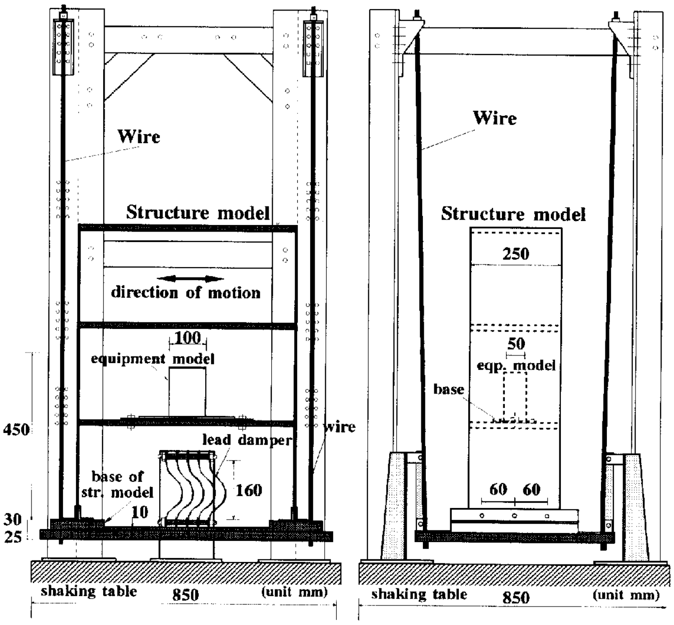

Figure 1. General layout of the experiment

Two kinds of ground excitations used in the experiments were two relatively strong motions (El Centro N-S 1940 and Hachinohe N-S 1968) and two very strong motions (Kobe N-S 1995 and Takatori E-W 1995) respectively on which actual dynamic characteristics are given in table 2. Figure 2 shows that those four ground excitations could be categorized into the excitations having shorter period components (El Centro N-S and Kobe N-S) which are close to the natural period of the actual main structure and those having longer period components (Hachinohe N-S and Takatori E-W) which are different from the natural period of the actual main structure.

Table 2: The main dynamic characteristics of used ground excitations (actual)

Characteristics	El Centro N-S	Kobe N-S	Hachinohe N-S	Takatori E-W
Main duration (sec)	60	11	40	15
Predominant period (sec)	0.2 – 5	0.25 - 1.4	0.3 - 3.0	0.8 - 2.0
Max. acceleration (gal)	341.70	-818.02	248.33	657.03
Max. velocity (cm/sec)	33.84	90.61	-36.21	127.01
Max. displacement (cm)	11.05	20.22	10.25	30.35

During the experimental works, the velocity of the very strong excitations (Kobe N-S and Takatori E-W) were reduced to be respectively 50 kine because of the shaking table limited capacity. Furthermore, during the resonance condition between the main structure model and nonstructural systems model, all the ground excitations were reduced to be sufficiently small (between 10 to 25 kine) in order to avoid an excessive acceleration response or occurrence of the damage on the nonstructural systems models. This procedure was considerably acceptable since the necessary output information desired to be presented is the amplification factors of acceleration rather than the maximum acceleration response itself.

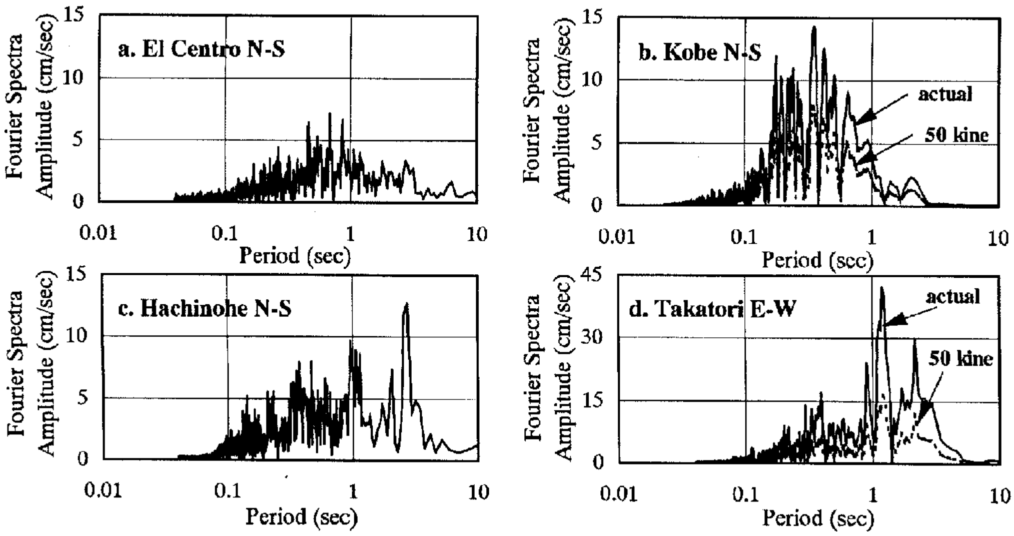

Figure 2. Fourier spectra of used ground excitations

The second stage experiments were conducted using the actual filing cabinet put on the shaking table surface which represented the main structure floors. Consequently the dynamic responses of floors of main structures (obtained from the first stage experiments) were adopted as the input excitation into the shaking table instrument after introduced some scale up factor into these excitations. In case of isolated nonstructural systems, the filing cabinet was mounted on the suspended isolation system (SPI) installed on the shaking table instrument. This SPI system has a fundamental period of 2.23 second and damping ratio of 13.2 %. Lay out of the experimental works was the same as those presented in figure 1 except that the main structure model was replaced by the filing cabinet which was directly placed on the SPI system. Table 3 shows the dynamic characteristics of the filing cabinet in case of fixed base condition and freely laid condition.

Table 3 : The dynamic characteristics of the filing cabinet

Condition	Damping Ratio (%)	Natural Period (sec)
Fixed base	13.00	0.4
Free standing base	16.50	0.5

THE ANALYTICAL WORK FOR MODEL TEST

The analytical works using *wilson-θ* integration method were conducted for both combined mass of structure – nonstructural systems and uncoupled structure – nonstructural systems [Sabol,1998][Soong,1995][Suarez and Singh, 1987]. In the combined method the main structure and nonstructural systems response are analyzed simultaneously while in the uncoupled method the main structure response is firstly determined without the existence of nonstructural systems afterwards this response is adopted as the input vibration for the nonstructural systems. Figure 3 shows the typical experimental and analytical results of the acceleration time history at top floor of 3DOF main structure model and the acceleration response time history of filing cabinet mounted on this floor in case of the El Centro N-S ground excitation. In this case the duration of floor acceleration time history was amplified with the scale factor of 5/2 since it constitutes the input vibration for the actual filing cabinet. It is clear that those results satisfactorily agree with each other. These analytical procedures can also be used to build response spectra of nonstructural systems as presented in figure 4 for each case of ground excitations. Several cases of damping factor of equipment model mounted on top floor of 3DOF structure are presented in this figure. The maximum acceleration response significantly decrease when damping factor increase which indicate that nonstructural systems response strongly depend on its damping factor.

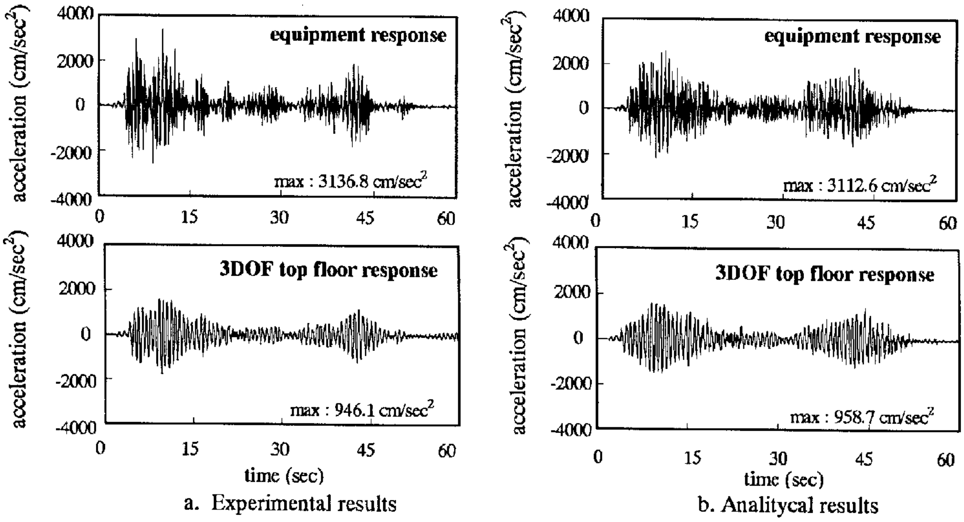

Figure 3. Typical acceleration response time history of main structure model and equipment model

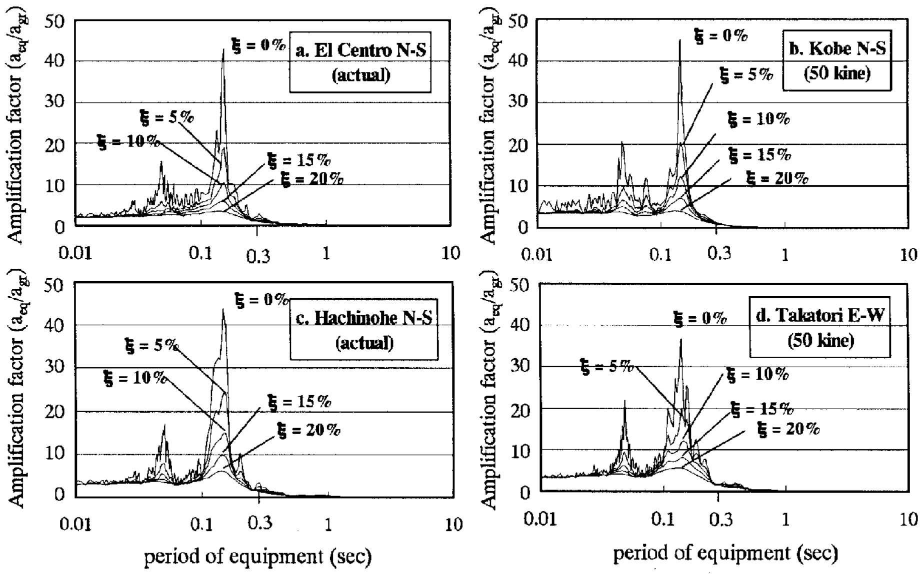

Figure 4. Acceleration Response Spectra of equipment model

THE EXPERIMENTAL RESULTS

Figure 5 shows the acceleration amplification factors of nonstructural systems which resulted from the experimental works conducted using the models of building equipment fixedly mounted on floors of fixed base main structure and building equipment fixedly mounted on floors of isolated main structure. It is found that in the fixed main structure the very large amplification factors (between 20 to 40) occurred when natural period of nonstructural systems having low damping ratio (0.2 %) resonates to the first mode natural period of the main structure. It is noteworthy that El Centro N-S (10 kine) and Kobe N-S (15 kine) gave relatively the same amplification while Takatori E-W (25 kine) gave the lowest amplification. It indicates that amplifications do not depend on the strength level of ground motion but seems strongly be influenced by the period components of ground excitations. When the period components of ground motion become close to the fundamental period of main structure (as the case of El Centro N-S and Kobe N-S) amplification become tremendously large. In case of nonstructural systems mounted on floors of isolated structure, the amplification factors are substantially low (around 2.2 to 2.6) even though in the very low damping ratio of both equipment model and main structure model. The amplifications are 1/8 to 1/18 times reduced from those in case of fixed base main structure.

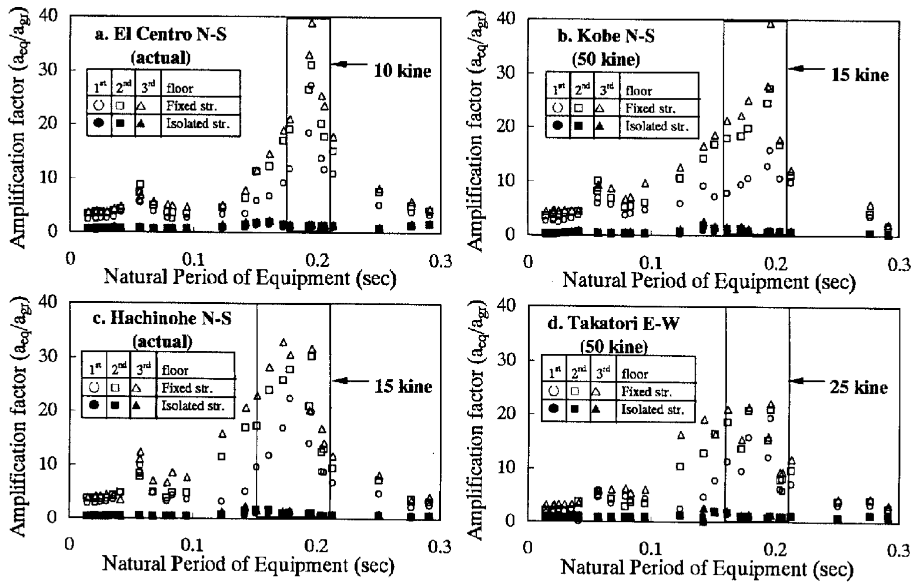

Figure 5. Amplification factors of equipment model mounted on fixed and isolated structure model

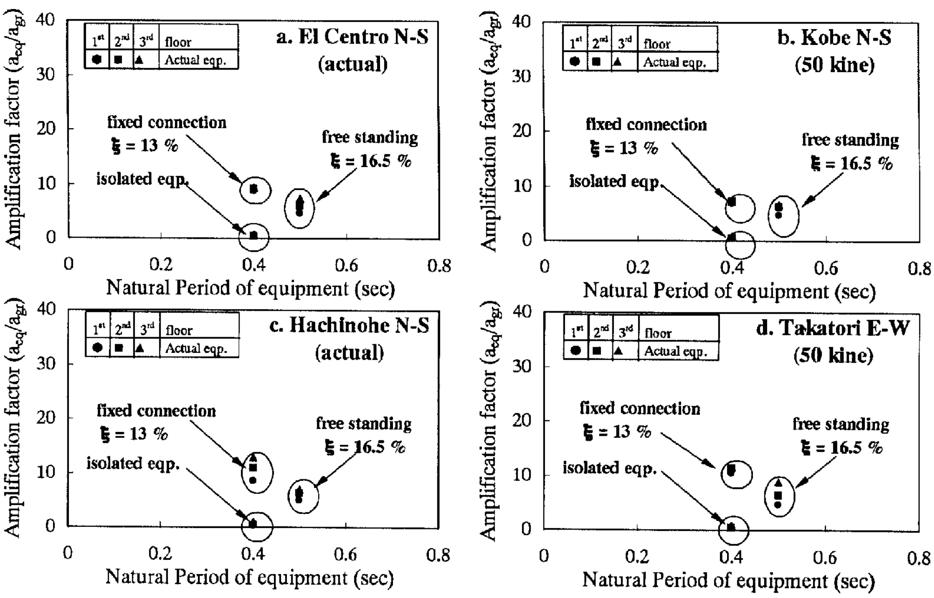

Figure 6. Amplification factor of actual filing cabinet for each type of connection to the floor surface

Figure 6 show the amplification factor of acceleration of nonstructural systems which resulted from the experimental works using actual filing cabinet having three connection method to floor that are fixed connection, free standing connection and isolated filing cabinet respectively. It is noteworthy that damping factor of actual filing cabinet was much higher than those of equipment model, so that the amplification factors are substantially reduced. The fix connected filing cabinet with 13 % damping ratio shows the maximum amplification factor only around 7 to 12 while the free standing filing cabinet with 16.5 % damping ratio shows the maximum amplification factor only around 6 to 8. These amplification factors are very much lower than those of light damped building equipment (model) which are ranged from 20 through 40. The smallest amplification factors are given by the isolated filing cabinet that are only 0.8 to 0.9 (7.8 to 15 times lower than those of fixed filing cabinet). It can be seen that the free standing filing cabinet has slightly lower acceleration amplification factor than fixed filing cabinet, however some residual displacement after the vibration may become serious problem in this type of connection. On the other side the displacement relative to floor may also occur at the isolated filing cabinet so that it is necessary to prepare some adequate space for the movement of the isolation systems. Table 4 shows the maximum actual displacement of free standing and isolated filing cabinet under each ground excitation. From the entire experimental results it is clarified that providing a sufficient damping factor and proper anchor on the nonstructural systems may improve their seismic performance effectively. Since an adequate damping factor for all kind of nonstructural systems are not always available then the use of an isolation device to protect the main structures or nonstructural systems could be the best alternative solution.

Table 4. Actual displacement on free standing and isolated filing cabinet

Ground Excitation	Residual Displacement (cm) (free standing filing cabinet)	Displacement relative to floor (cm) (isolated filing cabinet)
El Centro N-S	18.1	7.6
Kobe N-S	29.7	12.2
Hachinohe N-S	17.3	5.1
Takatori E-W	36.5	11.3

COMPARISON BETWEEN EXPERIMENTAL RESULTS AND DESIGN CODES

Two design codes evaluated in this paper are 1997 Uniform Building Code [5] and 1997 Building Center of Japan [2] respectively. Figure 7 show the calculated design horizontal force coefficient of nonstructural systems distributed along the height of main structures (F_H/W). The 3 story building (the same as that evaluated in the experimental works) is selected for an example. The maximum horizontal force coefficient at top floor is 2.64 for 1997 UBC and 2.0 for 1997 BCJ. It is noteworthy that neither UBC'97 nor BCJ'97 consider the damping factor of main structures or nonstructural systems, however in the practical use it is assumed that the damping ratio of main structures vary from 2 % to 20 % [Dowrick, 1978][Paz, 1985] while those of nonstructural systems may have more wide range. Since damping ratio of the main structure used in the experimental work was 0.5 % then some reduction factor as presented in table 6 should be introduced to obtain the actual seismic response of main structure having damping ratio of 2 % to 20 %. The reduction factors are calculated from the relationship between the maximum acceleration response and damping ratio of main structure given in figure 8. On the other hand the ground excitations in the experimental works during the resonance condition were reduced to be 10 kine through 25kine

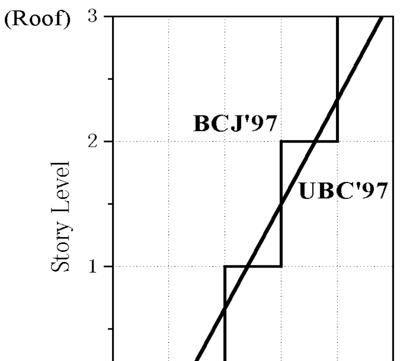

Figure 7. The horizontal force of nonstructural system stipulated in 1997 UBC and 1997 BCJ

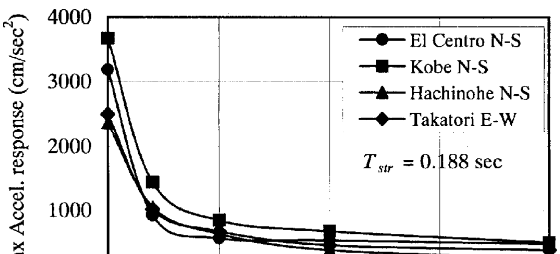

Figure 8. Maximum Acceleration Response vs damping ratio of main structure

Table 6. The reduction factors of maximum acceleration response of main structure

Ground excitation	$\xi = 2$ %	$\xi = 5$ %	$\xi = 10$ %	$\xi = 20$ %
El Centro N-S	2.84	4.67	4.95	5.43
Kobe N-S	2.17	3.69	4.62	6.19
Hachinohe N-S	1.93	3.24	5.31	7.65
Takatori E-W	2.09	3.16	4.64	5.51

then an extrapolation should be conducted to estimate the real horizontal force coefficient of actual nonstructural systems under the actual ground excitations. Figure 9 shows the horizontal force of actual building equipment having damping ratio of 0.2 % fixedly mounted on floors of fixed base main structure and the horizontal forces stipulated in two design codes. Almost all horizontal force of such equipment are larger than the maximum stipulated values for any kind of structure damping. It therefore becomes a warning that the design codes may not provide adequate safe design forces for such extreme cases and it is important to conduct a special treatment to secure these equipment against the seismic force, for example using an adequate anchor bolts [Masopust, 1998]. In case of actual filing cabinet having high damping ratio the horizontal force are drastically reduced as shown in figure 10 and figure 11. It is clear that the damping factor is very important for the attempt to get the low seismic response of nonstructural systems. When an adequate damping for the nonstructural systems is not possible then the utilization of isolation systems may be the best way to get significantly small horizontal force

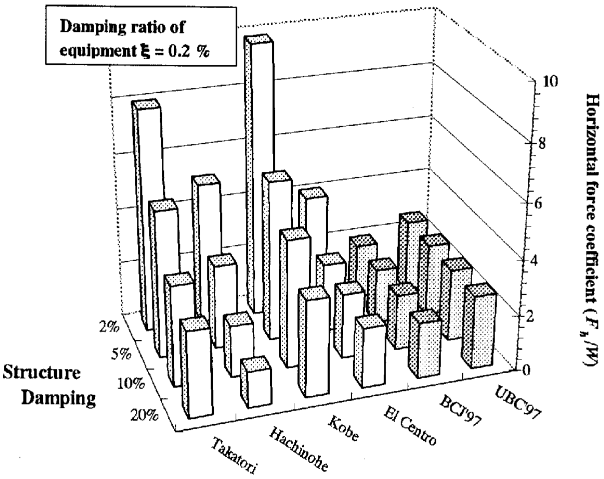

Figure 9. Horizontal force of actual equipment fixed on top floor of fixed base main structure

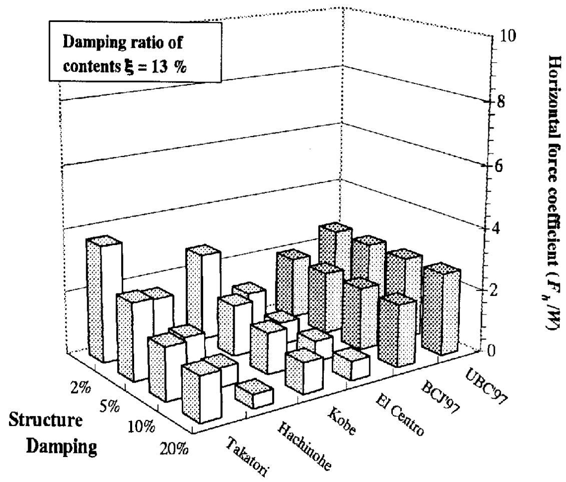

Figure 10. Horizontal force of actual contents fixed on top floor of fixed base main structure

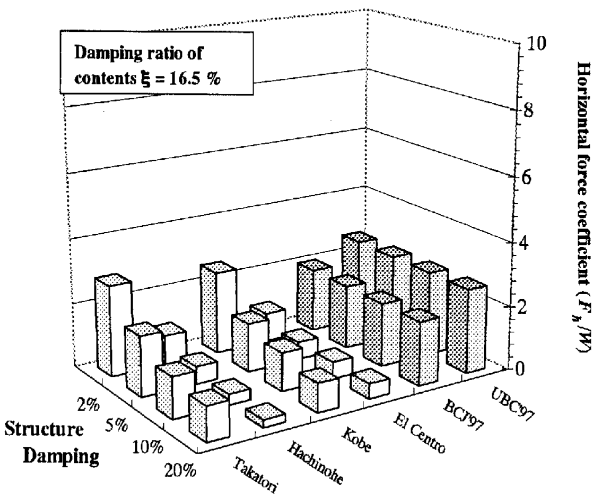

Figure 11. Horizontal force of actual contents freely put on top floor of fixed base main structure

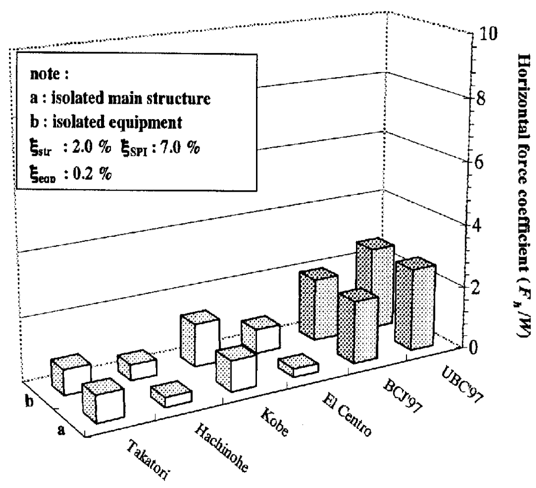

Figure 12. Horizontal force of actual equipment in case of the utilization of isolation system

as presented in figure 12. In this case the damping ratio of nonstructural systems and main structure are 0.2 % and 2 % respectively. Since the main structure model damping ratio was 0.5 % the assumption using reduction factor written in table 6 is again carried out to find the acceleration response in corresponding with the damping ratio of 2.0 % for actual main structure. Similarly, the damping ratio of filing cabinet was 16.5 % so that some multiplication factor based on the relationship between maximum acceleration vs nonstructural systems damping is used to estimate the acceleration response in corresponding with 0.2 % damping ratio. This multiplication factor can be obtained using the relationship between damping ratio and maximum acceleration response as shown in figure 4. Figure 12 shows that even though the main structure and nonstructural system damping ratio were very low (2.0 % and 0.2 %) the horizontal forces of nonstructural systems are relatively small and satisfy the maximum stipulated design force of both codes. It is expected that in case of real structures with larger damping ratio, the horizontal force of nonstructural systems should be much smaller than those resulted from the experimental works.

CONCLUSIONS

The dynamic response of nonstructural systems are strongly influenced by the dynamic response of floors of main structures where they are mounted as well as by the characteristics of ground excitations. The tuned condition between the fundamental period of a main structure and nonstructural systems or between predominant period of ground excitation and main structure fundamental period would cause a tremendously large acceleration amplification on the nonstructural systems. In some extreme cases the horizontal forces that occurred on the nonstructural systems may be larger than those stipulated in the design codes, which cases need special attention in associated with the safe design and construction.

As required in the performance based deign where both main structure and nonstructural systems should exhibit a good performance under the major earthquake, it will be clear that providing an adequate damping factor for both structure and nonstructural systems is very important to attenuate the seismic response of nonstructural systems. In fact, it is not always possible to provide a sufficient damping for every kind of nonstructural systems where some of them have very low damping factor so that result in the large seismic response. In this case the usage of isolation systems installed at base of main structure or directly at nonstructural systems may be the best way to solve the problem of large acceleration response of both a main structure and nonstructural systems.

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