Proceedings of

ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control

San Francisco, California
March 11-12, 1993

Volume 1: Seismic Isolation Systems

by

APPLIED TECHNOLOGY COUNCIL
555 Twin Dolphin Drive, Suite 550
Redwood City, California 94065

Funded by

NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
State University of New York at Buffalo
Grant Numbers 89-6003 and 91-5521

and

NATIONAL SCIENCE FOUNDATION
Washington, DC

STEERING COMMITTEE

Ian G. Buckle (Co-Chair)
Christopher Rojahn (Co-Chair)
Robert E. Bachman
Nicholas F. Forell*
Robert D. Hanson
Gary C. Hart
James M. Kelly
Ronald L. Mayes
Roland L. Sharpe
T. T. Soong

*ATC Board Representative

1993

Seismic Isolation System Design Procedure in Japan and its Comparison to the U.S.

Shoichi Yamaguchi[1], Hiroshi Akiyama[2]
Akira Wada[3] and Toshiyuki Nakazawa[1]

1) Tokyo Kenchiku Structural Engineers
2) University of Tokyo
3) Tokyo Institute of Technology

Abstract

This paper first presents the current states of seismic isolated buildings in Japan and mentions their background briefly. We also overview the present design procedures and refer to their problems. Then we introduce a part of research performed by AIJ-subcommittee and propose simplified design procedure based on this research. We tried to compare UBC'91 and Japanese current design on certain items and point out the differences and problems.

1. Introduction

Japan has suffered a great number of disasters from earthquakes in its recorded history. From the documents about earthquakes, we found that the damages caused by fire were much more serious than the damages caused by building collapse. The damages of Tsunami were also written. But we hardly obtain any practical techniques for reducing earthquake damages from these documents.

It was only about one hundred years ago, at the end of 19th centuries when swift flow of European civilization came into Japan, that prevention of these disasters began to be recognized as social problems.

In the December 1891 issue of the journal published by the Architectural Institute of Japan (AIJ), we can see the construction report [1] of a base isolated building by Kouzou Kawai. This report exactly shows the principle of seismic isolated buildings from today's viewpoint. Considering that seismic design technologies were undeveloped in those days, we could say that the intuitive idea of "decoupling a building from the ground would be effective for seismic safety" existed from old days.

The opening sentence of Mr. Roland L. Sharpe's paper [2] can be also applied to Japanese situation: "*The development of seismic design practice and codes in the United States are a direct result of the loss of lives, damage, and economic impact caused by major earthquakes.*" But the influences of earthquake disaster to a society differ from each other according to its history and customs.

On the other hand in modernized society, cities and their infrastructures have much more similarities than ever. There should be many common points in earthquake engineering between the U.S. and Japan nowadays. Particularly, concerning seismic isolation as a new structural system, both countries have the same standpoint in the development of structural design and practice. We think the exchange of correct technology information and the discussion for the future research are very important. Thus first we overview Japanese current states and then propose simplified design procedure based on it. In the last part, we study and make comments on the design procedure of UBC'91.

2. Review of practical design through BCJ's committee

The first seismic isolated building using laminated rubber bearings was built in Japan in 1983. From 1983 to 1992, about 67 buildings have been designed and many of them constructed. Before realizing a seismic isolated building, the plans must be examined by the Technical Committee of Base Isolated Structures of the Building Center of Japan (BCJ). This special examining system was introduced because such structures are not covered by the Japanese Building Standards Law.

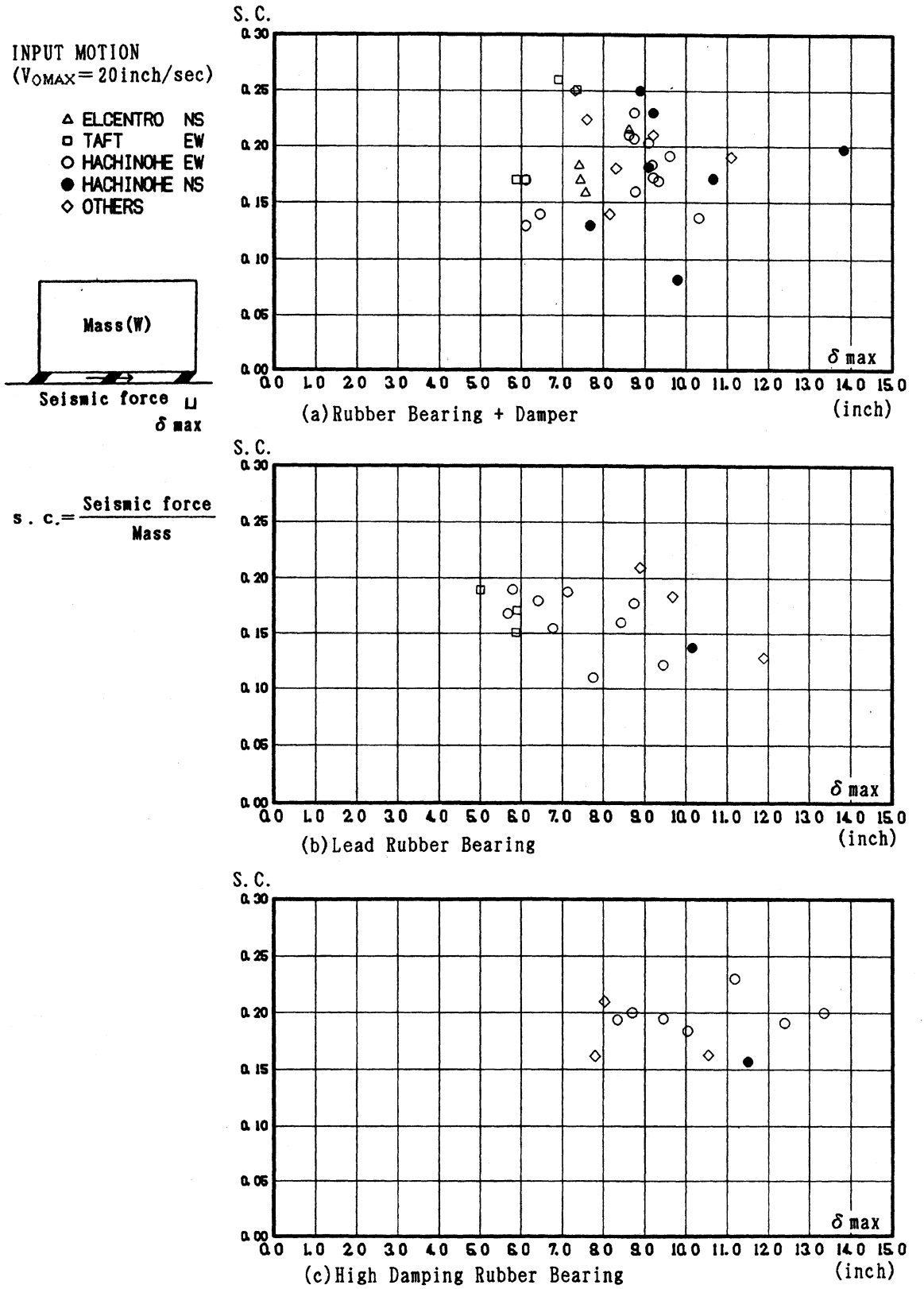
The BCJ publishes an information journal "Building Letter" monthly, from which we can get information about accepted buildings. By reviewing the characteristics approved by BCJ committee, it seems that certain rules equivalent to regulations have been established, although they have not yet been officially stipulated.

In principle, neither a compulsory design concept nor a procedure is required by the committee. The committee examines the submitted documents for judging the structural feasibility of the design. The committee does request time history response analyses using a number of horizontal input ground motions (not less than four recorded events), which act as a guideline in the review of the building's seismic capacity. The maximum velocity of the input ground motion is scaled to 10 inch/sec for Level 1 and 20 inch/sec for Level 2. The El Centro 1940 NS or Taft 1952 EW earthquake is used as the standard input ground motion, and the Hachinoe 1968 EW earthquake is used as the input including relatively long-period components. A recorded earthquake at the site or artificial ground motions which represent the ground characteristics at the site are used. The input ground motions of the El Centro, Taft, and Hachinoe earthquakes are applied to all buildings — that is, the design should cover the maximum response of those input ground motions. Accordingly, it can be said that input ground motions are tentatively specified by BCJ committee.

The maximum response values of accepted 63 buildings are plotted in Fig.1:

(a) buildings which use laminated rubber bearings with various dampers
(b) buildings which use laminated rubber bearings embedded with lead plugs
(c) buildings which use high-damping laminated rubber bearings

where x-coordinate is the maximum displacement and y-coordinate is the shear coefficient at the isolation interface. Although the reason for the scatter of data is not clear, the following rough



F i g. 1 Shear coefficient-displacement relation at isolation interface (BCJ 63 Buildings)

conclusions could be obtained from Fig.1:

1) Various seismic isolation systems are used because of different building scales and site conditions.
2) Time history response is sensitive to the vibration model and input motion.

Although some people have questions about this uniform design procedure, alternative input ground motions and design procedures have not yet been agreed on among the people concerned.

Input ground motion is fundamental in the seismic design of both seismic isolated buildings and ordinary buildings. A seismic isolated structure is a simple system in which input energy is concentrated on the isolation interface.

Since the characteristics of the ground motion reflect the sensitivity of the response, the study of input ground motion has been stimulated. However, it would be still a long time before the problem can be solved scientifically.

3. Proposal of Simplified Design Procedure

The Seismic Isolated Structure Subcommittee of AIJ, which was established in 1986, published "Recommendations for the Design of Base-Isolated Buildings" in 1989, and has continued research activities.

The seismic input and response analysis group of the subcommittee, the group chair is H.Akiyama, proposes the concept of energy balance between input energy and accumulated energy in isolation system.

This basic concept is as follows:

1) The total energy input into a structure by an earthquake ground motion depends on the first natural period and the total mass of the structure, and is rarely changed by the mass distribution, strength distribution or stiffness distribution. The distribution of the total input energy depends mostly on the strength distribution and stiffness distribution of each story.
2) In a seismic isolated structure, most of input energy is concentrated on the isolation interface, and the accurate energy balance can be easily estimated.

Thus this structural system has a simple form in seismic design, and we propose a simplified design procedure. This procedure is performed by these three steps:

1) The seismic capacity of a seismic isolated building is expressed by the amount of energy that can be stored and absorbed by the isolation interface.
2) The destructive power of an earthquake is expressed by the energy input caused by ground motion.
3) The seismic safety or the degree of risk is judged by comparing 1) with 2).

Although this procedure is similar to conventional methods, 3) is specially relevant for the

seismic isolation system.

In practical design, the most fundamental issue is the structural characteristics of the isolation interface. These characteristics can be summarized as follows.

1) Stiffness of isolators: which can be expressed by the primary natural period of a building, T_f , assuming that the horizontal load is supported by isolators only.
2) Damping characteristics: which can be expressed by the coefficient of the yield shear force of dampers: α_s
3) Deformation limit of isolators and dampers:
$$d_{max} < d_u$$
where d_u is the ultimate deformation of isolators and dampers, d_{max} is the design maximum deformation.

Using these three parameters T_f , α_s and d_{max}, we can obtain the following equations, assuming that the system has bilinear characteristics.

$$V_c = \sqrt{V_{ce}^2 + V_{cp}^2}$$

$$V_{ce} = \sqrt{\frac{2W_e}{M}} = \frac{2\pi}{T_f} d_{max}$$

$$V_{cp} = \sqrt{\frac{2W_p}{M}} = \sqrt{\frac{2n\,(\alpha_s Mg)\,d_{max}}{M}} \approx 4\sqrt{\alpha_s g d_{max}}$$

Where,

V_c : seismic capacity of a seismic isolated building, which is expressed by the equivalent velocity of accumulated energy in an isolation interface (inch/sec)

V_{ce} : equivalent velocity of the energy stored by isolators (inch/sec)

V_{cp} : equivalent velocity of the energy absorbed by dampers (inch/sec)

W_e : energy stored by isolators (lb·inch) :

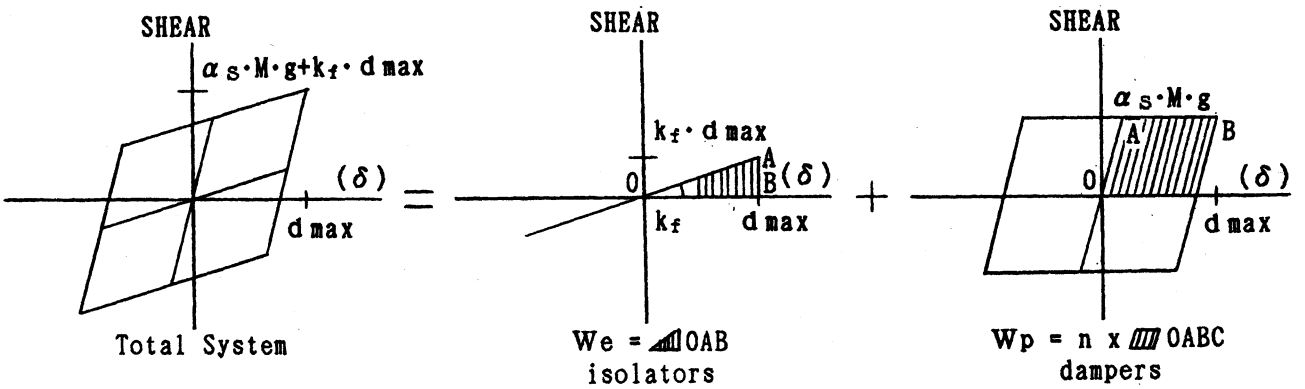
$$W_e = 1/2 K_f d_{max}^2$$ [See Fig.2]

W_p : energy absorbed by dampers (lb·inch) :

$$W_p = n\,(\alpha_s Mg) d_{max}$$ [See Fig.2]

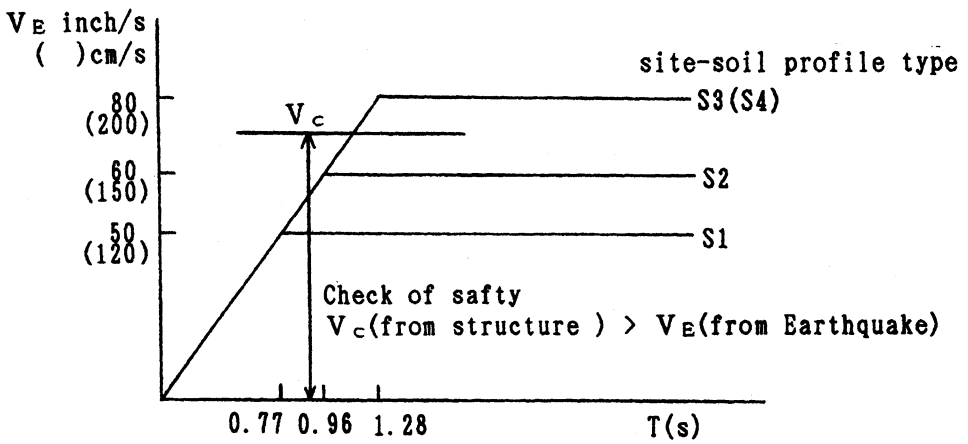
n : coefficient of accumulative plastic deformation ($n \approx 8$)

g : gravity acceleration (inch/sec^2)



F i g. 2 Energy stored by the isolation system

The energy accumulated in an isolation interface can be represented by V_C, and V_C represents the seismic capacity of a seismic isolated building. The seismic safety of the isolation interface is judged by comparing V_C with V_E. V_E is the equivalent velocity of the energy input due to ground motion. V_E corresponds to the velocity response spectrum (S_V) and is considered to be constant for relatively long periods (1.5 to 5 seconds). [See Fig.3]



F i g. 3 Energy input spectrum (AIJ's subcommittee)

4. Results of simplified design procedure applied to constructed buildings

Table 1 shows the calculated results of V_C and V_E of the buildings designed by Tokyo Kenchiku Structural Engineers. AIJ's subcommittee recommends the equivalent velocity V_E for different soil profile type as follows

Equivalent velocity V_E is : 50 inch/sec for S_1
60 inch/sec for S_2
80 inch/sec for S_3 (S_4)

The factor V_C/V_E is a seismic safety index. Table 2 shows the calculated results of the same buildings as Table 1, using the method of static lateral response procedure of the Appendix Division III of UBC'91.

UBC'91 asks for more strict deformation capacity than the Japanese one, but on the other hand UBC'91 used $3.0 \geq R_{wi} \geq 1.5$ and therefore the strength of a superstructure is lower than the Japanese one.

Table.1 Comparison between equivalent velocity of the total energy input by an earthquake (V_E) and equivalent velocity of the capacity of energy stored by the structure (V_C)

Simplified Design Procedure Method

BCJ No	Tf	αs	duf	dus	dmax	Vce	Vcp	Vc	Vclim	Vclim/Vc	SI	VE	Vc/VE	Vclim/VE	
			isoΔlim	damΔlim	Δlim/1.5	isolator	damper				soil type				
	sec		inch	inch	inch	inch/sec	inch/sec	inch/sec	inch/sec			inch/sec			
67	3.9	0.028	25.2	17.7	11.8	19.0	45.1	48.9	62.1	1.27	S1	50	0.98	1.24	○
57	2.8	0.047	22.4	15.7	10.5	23.5	55.0	59.8	76.0	1.27	S2	60	1.00	1.27	○
54	2.8	0.049	24.0	15.7	10.5	23.5	56.2	60.9	77.3	1.27	S2	60	1.01	1.29	○
44	3.0	0.052	24.4	15.7	10.5	21.9	57.9	61.9	78.1	1.26	S1+S2	55	1.12	1.42	○
32	2.3	0.055	15.4	13.8	9.2	25.1	55.8	61.2	78.0	1.28	S2	60	1.02	1.30	○
24	3.0	0.065	15.7	13.8	9.2	19.3	60.7	63.6	79.7	1.25	S2	60	1.06	1.33	○
18	2.9	0.039	22.4	13.8	9.2	19.9	47.0	51.0	64.8	1.27	S1+S2	55	0.93	1.18	○
14	2.2	0.045	15.4	13.8	9.2	26.3	50.5	56.9	73.3	1.29	S2	60	0.95	1.22	○
8	2.2	0.038	15.4	13.8	9.2	26.3	46.4	53.3	69.1	1.30	S2	60	0.89	1.15	△
7	1.9	0.043	16.5	13.8	9.2	30.4	49.3	57.9	75.7	1.31	S1+S2	55	1.05	1.38	○
2	2.1	0.035	15.4	13.8	9.2	27.5	44.5	52.3	68.4	1.31	S2	60	0.87	1.14	△
0	1.8	0.040	9.4	9.4	6.3	21.9	39.3	44.9	58.2	1.30	S2	60	0.75	0.97	△

Tf : The primary natural period of base isolated building (isolaters only)
αs : Damping characteristics (the coefficient of the yield shear force of dampers)
duf : Ultimate deformation of the isolator
dus : Ultimate deformation of the damper
dmax : Design deformation of the isolator or the damper (maximum deformation of isolation interface)
Vce : Equivalent velocity of the energy stored by isolators
Vcp : Equivalent velocity of the energy absorbed by dampers
Vc : Seismic capacity of a seismic isolated building, which is expressed by the equivalent velocity of the accumulated energy in the isolation interface
Vclim : Equivalent velocity of the accumulated energy in the isolation interface to ultimate deformation of isolation interface
SI : Soil profile type
V_E : Equivalent velocity (Value of JIA Recommendation decided by soil profile type)

○ Applicable
△ Alternative proceedures are needed
* Not applicable

$$V_E = \sqrt{\frac{2E}{M}}$$

V_E : Equivalent velocity
E : Energy
M : Mass

T a b l e . 2 Results for the same buildings as TABLE.1, using the method of static lateral response procedure of the Appendix Division III of UBC'91

US-Recommendation

BCJ.No	Z	N	SI	TI	B	D	DT	DTM	duf	dus	du/DTM		kmax/W	Vb /W	Vs /W
					β		D*1.15	DT*1.5	isolator	damper			kmean*1.2	kmax*D/1.5	kmax*D/Rwi
				sec		inch	inch	inch	inch	inch			1/inch		
67	0.4	1.0	1.00	3.68	1.35	10.9	12.6	18.8	25.2	17.7	0.94	○	0.01091	0.08	0.04
57	0.4	1.0	1.50	2.65	1.34	11.9	13.7	20.5	22.4	15.7	0.77	△	0.02102	0.17	0.08
54	0.4	1.0	1.50	2.64	1.35	11.7	13.5	20.2	24.0	15.7	0.78	△	0.02125	0.17	0.08
44	0.4	1.0	1.25	2.79	1.35	10.3	11.9	17.8	24.4	15.7	0.88	△	0.01900	0.13	0.07
32	0.4	1.0	1.50	2.21	1.30	10.2	11.7	17.6	15.4	13.8	0.78	△	0.03038	0.21	0.10
24	0.4	1.0	1.50	2.59	1.50	10.3	11.9	17.8	15.7	13.8	0.77	△	0.02212	0.15	0.08
18	0.4	1.0	1.25	2.74	1.34	10.2	11.8	17.7	22.4	13.8	0.78	△	0.01968	0.13	0.07
14	0.4	1.0	1.50	2.18	1.20	10.9	12.5	18.8	15.4	13.8	0.73	△	0.03123	0.23	0.11
8	0.4	1.0	1.50	2.21	1.20	11.1	12.7	19.1	15.4	13.8	0.72	△	0.03031	0.22	0.11
7	0.4	1.0	1.25	1.94	1.15	8.4	9.7	14.5	16.5	13.8	0.95	○	0.03960	0.22	0.11
2	0.4	1.0	1.50	2.14	1.15	11.2	12.8	19.3	15.4	13.8	0.72	△	0.03239	0.24	0.12
0	0.4	1.0	1.50	1.81	1.15	9.4	10.8	16.2	9.4	9.4	0.58	*	0.04549	0.29	0.14

Z : Numerical coefficient related to the seismicity of a region (Assuming Z=0.4)
N : Numerical coefficient related to the proximity of the building or structure to active faults (Assuming N=1.0)
SI : Numerical coefficient for site-soil profile
TI : Period of seismic-isolated structure
B : Numerical coefficient related to the Effective Damping of Isolation System
D : Design Displacement
DT : Total Design Displacement (Assuming Coefficent of torsional effect=1.15)
DTM : Total Maximum Displacement (DTx1.5)
duf : Ultimate deformation of the isolator
dus : Ultimate deformation of the damper
du : Design's deformation of the isolator or the damper (maximum deformation of base-isolated story)
k_{max} : Maximum effective stiffness of the isolation system
W : The total seismic dead load
Vb : The total latelal seismic design force or shear below the isolation interface
Vs : The total lateral seismic design force or shear above the isolation interface

○ Applicable
△ Alternative proceedures are needed
* Not applicable

5. Consideration of Differences between the U.S. and Japan

In static lateral response procedure of UBC'91, a design displacement is defined as:

$$D = 10 \cdot Z \cdot N \cdot S_I \cdot T_I / B \quad \text{(inch)} \quad \text{[See Fig.7]}$$

A design displacement can be regarded as a displacement response spectrum which has the parameters of Z, N, S_I, B and is in proportion to T_I. The equivalent velocity response spectrum S_V becomes

$$S_v = D\frac{2\pi}{T_I} = 62.8 \cdot Z \cdot N \cdot S_I / B \quad \text{(inch/sec)}$$

When the standard values of these parameters are specified as $Z = 0.4$, $N = 1$, $S_I = 1$ and $B = 1$, we obtain

$$D = 4T_I \quad \text{(inch)}$$
$$S_V = 25.1 \quad \text{(inch/sec)}$$

In Japan, design seismic loads of ordinary buildings for severe earthquakes, though they are not applied to seismic isolated buildings, are defined by C_B, a design base shear coefficient of ultimate bearing capacity, as shown in Fig.4.

For a structure with $T > 0.8$ sec, C_B is prescribed by the formula, applying the Japanese equivalent values of Z, S_I and D_S (B and N are not defined).

$$C_B = (0.64 / T) \cdot D_S.$$

D_S is a reduction factor derived from structural plastic deformability and damping effect. The value of 0.25 is specified for the most ductile structure and 0.55 for the least ductile structure, except brick structures and plain concrete structures. Assuming that $D_S = 1.0$, S_V and S_D are calculated as:

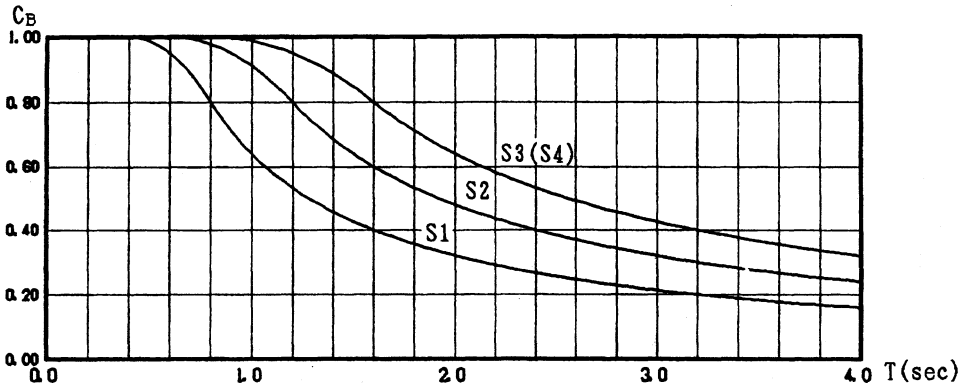
$$S_V = 39.4 \quad \text{(inch/sec)} \quad \text{[See Fig.5]}$$
$$S_D = 6.3T \quad \text{(inch)} \quad \text{[See Fig.6]}$$

Considering the effect of energy absorption, and assuming that $D_S = 0.4$, S_V and S_D are calculated as:

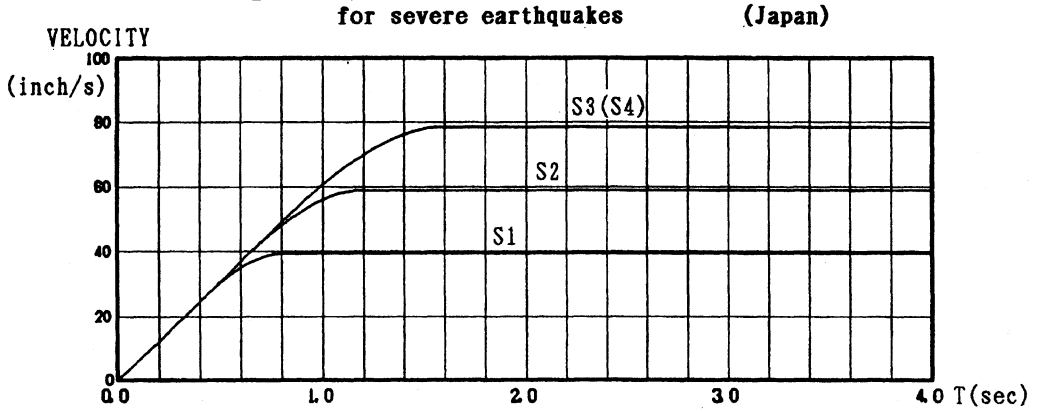
$$S_V = 15.8 \quad \text{(inch/sec)}$$
$$S_D = 2.5T \quad \text{(inch)}$$

Consequently, the calculated values of the first case are over estimated and the second ones are relatively small compared to the results of the time history response analysis.

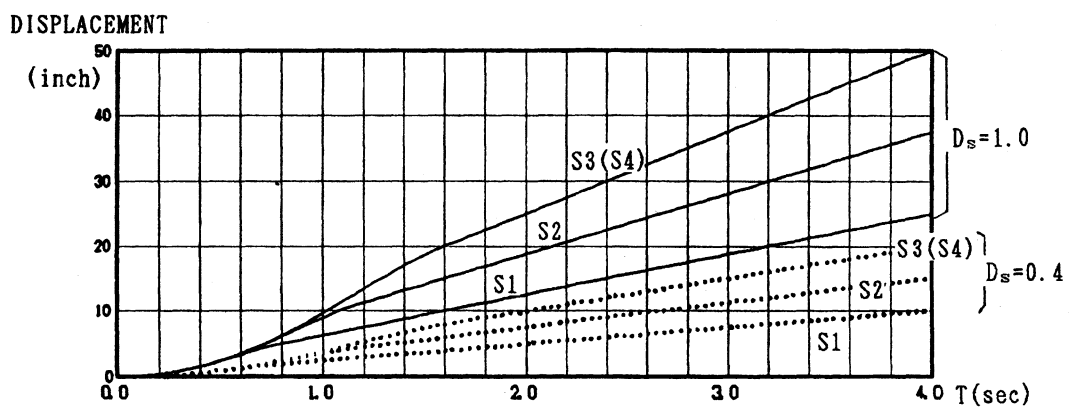
When we adjust this formula to UBC'91, approximately $D_S = 0.65$ is obtained by calculating backward. This result is relatively large compared to the results of Japanese current time history response analysis.



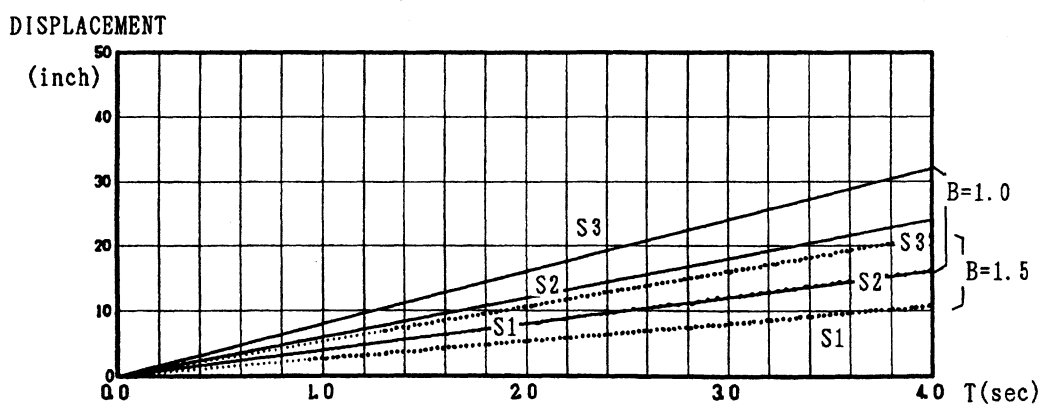
F i g. 4 Spectrum of Base Shear Coefficient for severe earthquakes (Japan)



F i g. 5 Velocity Response Spectrum (Japan)



F i g. 6 Displacement Response Spectrum (Japan)



F i g. 7 Design Displacement of UBC'91 (Z=0.4, N=1.0)

On the other hand in UBC'91, we have a question that the value $R_{WI}(MAX) = 3.0$ might be too large, which is used for calculating the total lateral seismic design force for a superstructure. This is because seismic isolation system is based on the concept "energy input is designed to be concentrated on an isolation interface". The idea of expecting the energy absorption capacity by superstructure's plastic deformation does not meet this basic concept. Contrarily in Japan, we do not use the reduction factor for lateral design force of a superstructure.

Here we present our opinion about two features of seismic isolation system. In Fig.1, the coefficients of response shear force are plotted between 0.1 to 0.25, and these values are small enough compared to the standard coefficient 1.0 of ordinary fixed buildings. This is the first feature of seismic isolation system.

A seismic isolated structure usually has a long natural period 2 to 4 sec and vibrates slowly. A superstructure itself has a comparatively short natural period less than 1.0 sec. We can say that the lateral force acts to a superstructure as the static external forces. Therefore, a superstructure should have efficient static strength which exceeds the response shear force. Large deformability is not required for a superstructure. Thus a superstructure is free from various restrictions for securing deformability, and is only required to have small strength such as 0.1 to 0.25 shear coefficient. This is the second feature.

6. Conclusion

The contents of UBC'91 have many excellent points. On the other hand, our proposal also has the practical meaning for structural engineers, because the absorption and accumulation of energy input can be expressed visually with simple formulas and parameters. But we should continue to study on more correct estimation of energy input into a structure and absorbed energy by isolation devices.

7. References

1) K. Kawai, 1891, Journal of Architecture and Building Science, No.60
2) R. L. Sharpe, 1991/12, "Earthquake Disasters and Changes in United States Seismic Design Building Codes", Proceedings of the IDNDR International Symposium on Earthquake Disaster Reduction Technology
3) The Building Letter, the Building Center of Japan
4) H. Kitamura and H. Akiyama, 1992/4, "Seismic response prediction for base-isolated building by considering the energy balance", Proceedings of international workshop on recent developments in base isolation techniques for buildings, Tokyo, A.I.J
5) The Appendix Division III static lateral response procedure , Uniform Building Code 1991