

PERFORMANCE BASED DESIGN OF SEISMICALLY ISOLATED BUILDINGS IN JAPAN

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ABSTRACT

The seismic isolation system is a structurally applicable construction method for newly constructed buildings and existing buildings for retrofitting. A lot of seismically isolated (SI) buildings have sprung up in Japan, totaling approximately 2,500 at present. Condominium with SI accounts for 45% of that, and retrofitting accounts for approximately 4 %. The number of houses with SI is more than 3,500. Notification No. 2009 “Calculation Method for SI Buildings” was issued in 2000 as the equivalent linear method (ELM). The time history analysis method (THAM) was common before 2000. The number of SI buildings by ELM is gradually increasing, 15% of all SI buildings. This paper shows the calculation procedure by ELM. Important matters for calculation are explained with a flow-chart, while showing an example of a building with SI.

1. INTRODUCTION

Since the 1994 Northridge earthquake in the USA, the 1995 Hyogoken-Nanbu earthquake in Japan, the 1999 Chi-Chi earthquake in Taiwan, the 2008 Wenchuan earthquake in China and the 2009 L'Aquila in Italy, the number of seismically isolated buildings have increased rapidly. Over the same period, building codes have been revised and updated to include requirements for design of seismically isolated buildings. In Japan, the most recent building code provisions took effect in 2000. In this paper, procedures and practice to conduct performance based design of seismically isolated buildings are introduced.

A two-stage design philosophy was introduced in the Japanese building code as shown in Table 1. The two stages are usually defined as damage limitation (Level 1, approximately a 50-years return period) and life safety limitation (Level 2, approximately a 500-years return period). In the damage limitation stage, the structural safety performance must be preserved in the considered earthquake. In the life safety stage, the building should not collapse to assure the safety of human life. The performance target can be classified into three parts: superstructure, seismic isolation layer and substructure, as shown in Table 1. In the Japanese code, the 5% damping spectral acceleration at bed rock site is defined. The site spectrum is obtained by considering the soil amplification factor, which is dependent on the soil profile. The time history analysis method is mostly popular to give best performance while equivalent linear method can be selected simply at limited conditions. Subsequently, a typical 7-story reinforced concrete building, isolated with a combination of rubber bearings, sliding bearings with elastomer and steel dampers, is analyzed to demonstrate the design practice.

Table 1 Performance Target of seismically isolated (SI) buildings

Frequency of External Disturbance		Rarely occurring event	Extremely rarely occurring event
Super structure	horizontal strength	Elastic	Elastic limited
	story drift angle	<1/500	<1/300
SI layer	Isolator	$\gamma < 100-150\%$	$\gamma < 150-250\%$ Tensile stress < 1N/mm ² within stable stress and deformation relation
	Damper	Standard deformation	Design limit deformation
Sub structure	horizontal strength	Elastic	Elastic
	story drift angle	1/1000	1/500

2. DESIGN PROCEDURE

2.1 Applicability of the equivalent linear analysis method

In Figure 1 is shown the choice of the calculation route following the Japanese code. The equivalent linear method (ELM) is used at limited conditions shown in Table 2 for buildings that are less than 60m high, that have SI layer located above the ground, and that have first or second class ground classification, etc. The time history analysis method (THAM) is possible for all buildings as follows.

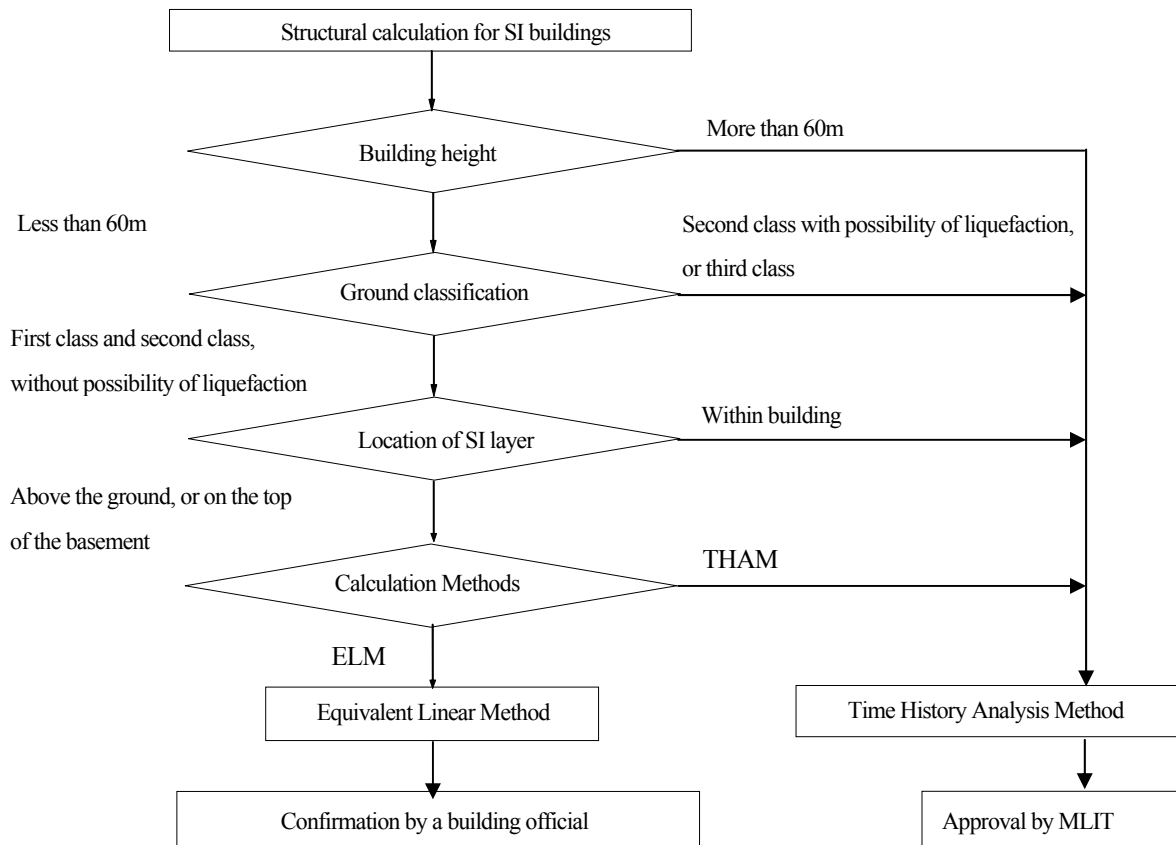


Figure 1 Choice of the calculation route

Table 2 Applicability of the equivalent linear analysis method

Limitation on ground class	1,2
Maximum height of superstructure	60m
Location of devices	Base only
Maximum mass-stiffness centers eccentricity	3%
Tension in isolator	Not allowed
Yield strength	$> 0.03W$
Period range of T_e	$T_2 > 2.5s$

2.2 Structural calculation procedure for SI buildings

In generally, the equivalent linear method (ELM) can be illustrated as follows. The base shear force is obtained from the spectral acceleration and weight as shown in Equation (1).

$$\delta = \frac{M F_h(h, T_e) S_a(T_e)}{K_e}$$

$$\delta_r = 1.1 \delta$$

$$\delta_r = \alpha \delta_r$$

$$Q_s = \gamma K_e \delta$$
(1)

where,

δ : design displacement of the isolation system

M : total weight of the building

$F_h(h, T_e)$: response reduction factor;

h : effective damping

$S_a(T_e)(g)$: site response acceleration considering site soil conditions

K_e : effective stiffness of the isolation system

δ_r : the maximum design displacement used to determine the clearance;

I : coefficient related to the eccentricity of the isolation system;

α, γ : safety factor related to variation of properties with temperature, ageing or products tolerances discrepancy introduced in the Japanese code;

Q_s : shear force in the base of the superstructure;

In general, the five percent-damped spectral acceleration, $S_a(T)$, is given by Equation (2).

$$S_a(T) = Z G_s(T) S_0(T)$$
(2)

where:

Z : the seismic hazard zone factor.

$G_s(T)$: a soil amplification factor dependent on the soil profile.

$S_0(T)$: the design spectral acceleration at engineering bedrock ($V_s > 400$ m/s) defined in Equation (3) which is shown in Figure 1 for Level 2 input.

$$S_0(m/s^2) = \begin{cases} 3.2 + 30T & T \leq 0.16 \\ 8.0 & 0.16 < T \leq 0.64 \\ 5.12/T & 0.64 < T \end{cases}$$
(3)

The site amplification coefficient $G_s(T)$ is defined in Figure 3.2 based on different site classes. However, in the engineering practice, the $G_s(T)$ is usually calculated iteratively based on the investigated V_s or N values and types for the soil profile rather than directly using the coefficients defined in the code. The zone coefficient Z is divided into four levels as 1.0, 0.9, 0.8 and 0.7 (Okinawa only) within Japan.

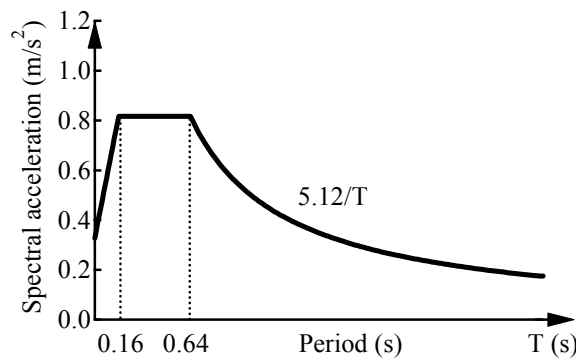


Figure 1 Design spectral acceleration at the engineering bedrock ($V_s > 400$ m/s)

The response reduction factor $F_h(h, T_e)$ is defined in Equation (4) by using the effective viscous damping of a fluid damper, h_v , and a hysteretic damper h_d which is decreased to 80 percent of the effective damping for a combined viscous-hysteretic system.

$$F_h = \frac{1.5}{1+10(h_v + 0.8h_d)}; \quad F_h \geq 0.4 \quad (4)$$

To use ELM, calculation model must appropriately evaluate one mass for superstructure and characteristics of isolation devices at supposed response range. Modeling of isolation devices must appropriately evaluate stiffness and damping characteristics based on the test data by manufacturer. The convergence procedure of the equivalent linear analysis method is shown in Figure 2. The procedure is summarized as follows:

- Assume a displacement of the isolation system, $D_{D0}(\delta_0)$.
- Calculate the effective stiffness, K_e , and effective damping, $\xi_e(h)$, of the isolation system, assuming a bi-linear model for the isolation system.
- Calculate the equivalent period, T_e , of the isolation system.
- Calculate the corresponding response reduction factor, $F_h(h, T_e)$, and the spectral acceleration, $S_d(T_e)$.
- Calculate a new isolation system displacement, $D_D(\delta)$, using Equation (1).
- Repeat the above steps until $D_D(\delta)$ converges.

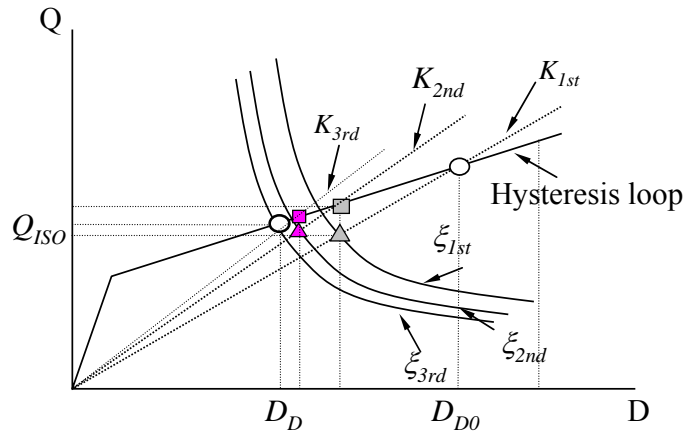


Figure 2 Illustration of the convergence procedure for the equivalent linear analysis method.

2.3 Synopsis of ELM

Step by step procedure to use ELM is summarized as follows.

1. Assumption for sections of frame members of the building

The item is done conventionally by structural engineers, such as on sections of beams, columns, walls and slabs in earthquake resistant buildings.

2. Selection of devices for seismic isolation

Devices for seismic isolation are selected from those approved by MLIT, and their performance is checked to determine, which are allowable compressive capacity, horizontal stiffness, ultimate deformation capacity, etc.

3. Arrangement of devices in SI layer

The item is the arrangement of devices, which must have an eccentricity-ratio in SI layer of 3% or less.

4. Setting of acceleration spectrum on the surface of the site

The setting of acceleration spectrum on the surface of the site is necessary for achieving displacement and shear force of SI layer. Therefore, soil property conditions on the site should be checked. The soil amplification factor $G_s(T)$ is usually calculated iteratively based on the investigated Vs or N values and types for the soil profile

5. Calculation of response displacement and shear-force of the SI layer

The item is calculation of response displacement and shear-force of the SI layer on the above spectrum with damping factor by using the design limit deformation based on the design limit period.

6. Calculation of shear-force of superstructure and substructure

The above shear-force is distributed to each story of the superstructure by using the distribution rule.

7. Evaluation of response values of SI layer from wind load

The item is evaluation of response values of SI layer for wind load on the restoring force-displacement curve of SI layer to confirm safety against extremely rare-occurring strong winds.

8. Confirmation of safety of devices for vertical load

The eighth item is confirmation of safety of devices against vertical load during earthquakes. Stress must be below allowable stress against vertical loads including up and down acceleration of 30% of a building own-weight. No minus stress is allowable for bearings.

9. Securing safety of connections of devices to structures

Securing of safety of connection of devices to structures, such as footings, capitals, girders and columns is important to make use of the performance of devices.

10. Confirmation of satisfaction of stipulations on SI system

Finally, SI system must satisfy stipulations, which are as follows:

Space is required to secure displacement, which includes response values and certain safety values, e.g. 20 cm. Movement of SI building must be maintained in heavy snow falls. Exchange of devices or checking devices must be possible, and a signboard or an indicator for “ this building is seismically isolated” is required.

2.4 Other important matters for SI buildings

The following items are other important matters other structures for SI buildings.

- Architectural Planning

(a) Planning of Isolation Layer

Architectural details in, or in the vicinity of the isolation layer must be planned so as not to cause injury to humans or damage architectural members, considering that the isolation layer deforms significantly during earthquakes.

(b) Fire Resistive Covering and Performance of Isolation Devices

The isolators must support superstructure without losing supporting capacity of vertical loads subjected to fires expected to happen in, or in the vicinity of the isolation layer.

Fire resistive covering must protect isolation devices until fire ends. It must follow the expected deformation without covering materials falling off. Also, it must be set so as not to interfere with maintenance of isolation devices.

- Planning of Equipment System

Equipment in the vicinity of the isolation layer must be planned in order for their functions to be maintained during earthquakes, considering large displacement at the isolation layer.

- Construction

Structural engineer must inform the constructor of design-demand requirements at construction stage. Also, construction supervisor must supervise the suggested construction planning and the undertaken construction, to provide expected performance as a seismically isolated building.

- Maintenance

Building owner must properly maintain own building after completion. Structural engineer must draw up maintenance plans and inform the owner so that the required seismic isolation performance is maintained during the building's lifetime.

3. DESIGN EXAMPLE OF A SEVEN-STORY RC BUILDING

Synopsis of ELM described in section 2.3 will be used to design the seven-story building.

3.1 Building Model

The outline of the building is shown below. The elevation, span-direction and longitudinal-direction draws are shown in Figure 3.1. Typical plan is shown in Figure 3.2.

Principal use	Condominium
Total floor area	1,470m ²
Maximum eaves height	22.0m
Classification of structure	Reinforced concrete structure
Structural type	X(lateral) direction : Moment frames Y(longitudinal) direction : Moment frames with bearing walls
Ground classification	Second class (T _g =0.34s)
Foundation	Direct

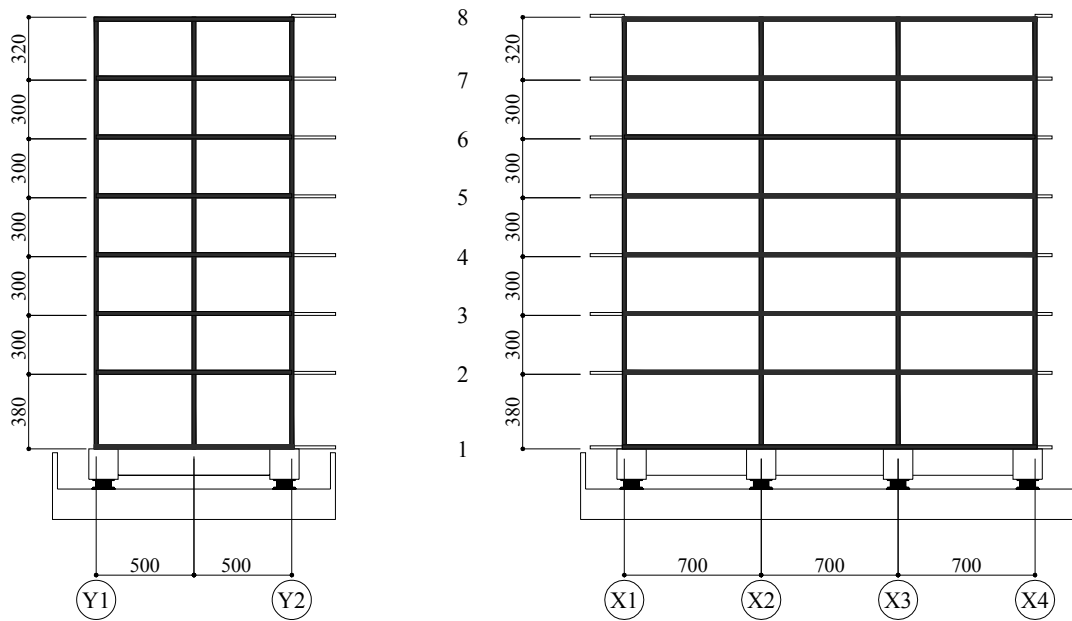
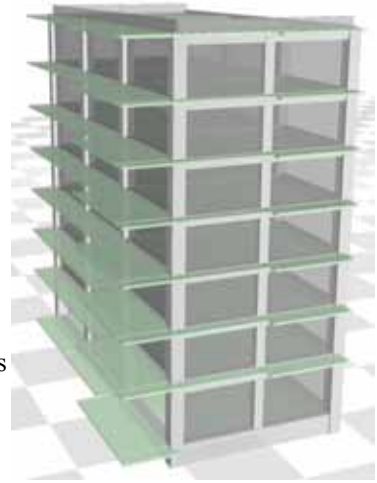


Figure 3.1 The elevation, span-direction and longitudinal-direction draws.

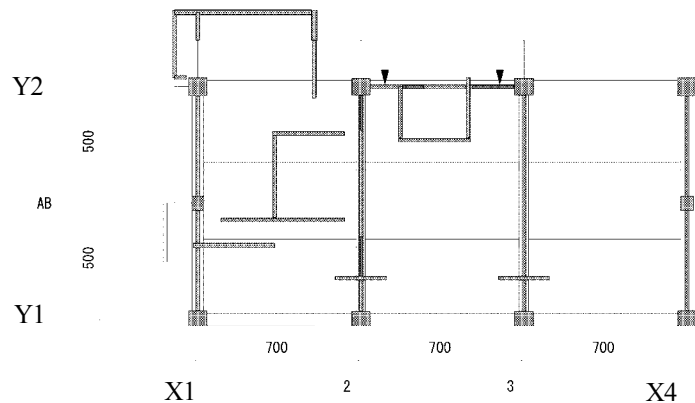


Figure 3.2 Typical plan of the building.

The story mass and horizontal stiffness of both X, Y direction of the building are summarized in Table 3.1. The fundamental periods of the fixed-base model are $T_x = 0.682s$ and $T_y = 0.258s$. The vertical loads of each column on isolation devices are summarized in Table 3.2.

Table 3.1 Story mass and the horizontal stiffness of the building.

	Height(m)	Weight (kN)	Horizontal stiffness (kN/mm)	
			X	Y
7	3.20	2854	325	1144
6	3.00	3328	449	2168
5	3.00	3293	488	2845
4	3.00	3331	560	3449
3	3.00	3379	635	4191
2	3.00	3390	720	5363
1	3.80	4220	778	10690
SI	1.50	4461		
Total		28256		

Table 3.2 Vertical loads on isolation devices (kN)

	X1	X2	X3	X4
Y2	4,363	5,161	4,659	2,975
Y1	2,539	3,767	3,728	2,504

3.2 Selection of devices for seismic isolation

Figure 3.4 shows the layout of isolation devices for the building. A combination of rubber bearings (RB80, RB80S), sliding bearings with elastomer (SC60, SC70) and steel dampers (SD) are selected to give a demonstration of the calculation procedure. The sketch of the used isolation devices is shown in Figure 3.3.

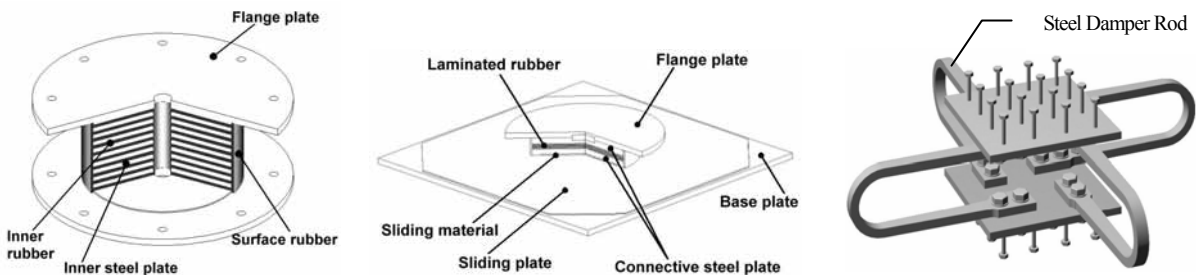


Figure 3.3 Sketch of the isolation devices (from left: rubber bearing, slider with elastomer, steel damper).

The characteristics of each device are shown in Table 3.3. The design displacement limit, δ_s , at the isolation interface is determined as the minimum value of the design displacement limit ${}_m\delta_d$ for all components of the isolation system. The design displacement limit ${}_m\delta_d$ for each device is obtained by multiplying the safety factor β by the ultimate deformation δ_u for each device. The value of the safety factor β is based on empirical knowledge resulting from experimental data obtained in Japan. A typical example of determining ${}_m\delta_d$ for a rubber bearing and slider with elastomer is shown in Figure 3.4. This figure shows that the bearing must be designed within the limits of vertical stress, horizontal displacement, and limitation by buckling of bearing. In Figure 3.4, ultimate deformation δ_u is derived from 1/3 of ultimate vertical design strength F_c . For typical devices, safety factors are given as follows:

- $\beta=0.8$, for elastomeric isolator;
- $\beta=0.9$, for sliding bearing and rotating ball bearing;
- $\beta=1.0$, for damper and restorer.

Table 3.3 Characteristics of isolation devices

Name		Rubber Bearing		Slider with Elastomer		Steel Damper
Type name		RB80S	RB80	SC60	SC70	SD-U
G	N/mm ²	0.39	0.39	0.78	0.78	
Diameter	mm	800	800	600	700	45
Rubber Thickness	mm	6	6	5	5	
Number of sheet		33	30	4	4	
Total thickness	mm	198	180	20	20	
S ₁		31.7	31.7	29	33.5	
S ₂		4.0	4.4	30	35	
Unloading stiffness K ₁	kN/mm	0.99	1.09	11	15	7.6
Post yielding stiffness K ₂	kN/mm	0.99	1.09	0	0	0.128
Friction Factor		-	-	0.011	0.011	-
Yield load Q _y	kN	-	-	41.2	54.0	184
Vertical Stiffness	kN/mm	2,480	2,730	10,600	14,400	-
Tensile Strength	kN	501	501	0	0	-
Allowable Stress	N/mm ²	10	10	17	17	
Allowable Load	kN			3,748	4,910	0
Ultimate compressive strength σ_{cr}	N/mm ²	44	49	57	57	-
F _c	N/mm ²	41	44	51	51	
ultimate deformation δ_u	m	0.679	0.603	0.55	0.55	0.65
safety factor β		0.8	0.8	0.9	0.9	1.0
design displacement limit ${}_m\delta_d$	m	0.543	0.482	0.495	0.495	0.65

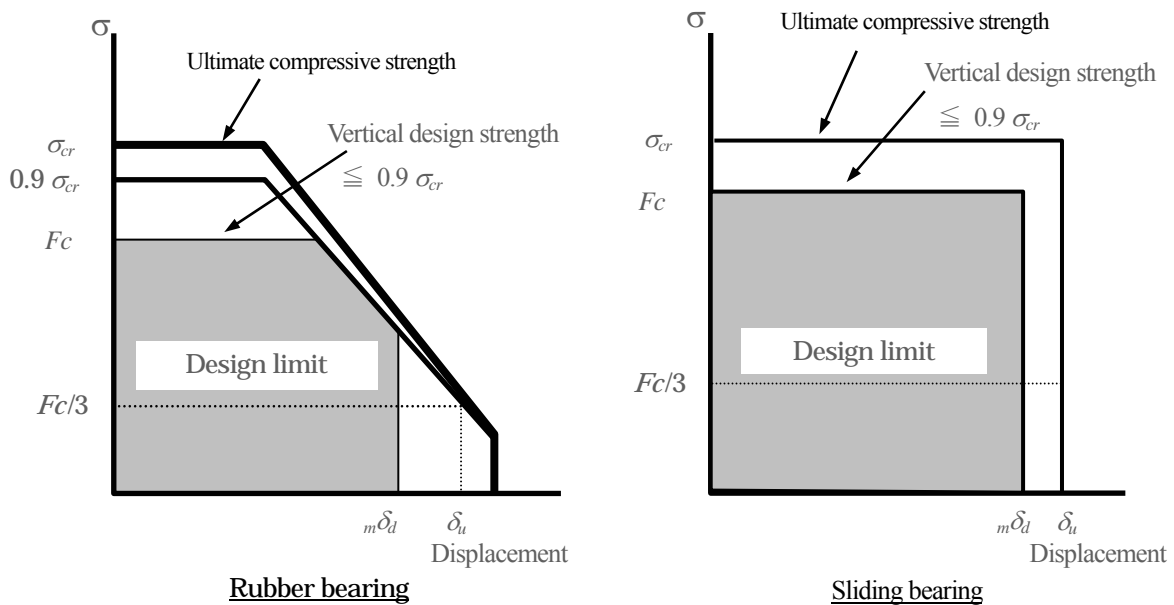


Figure 3.4 Design displacement limits for a rubber bearing and slider with elastomer.

3.3. Arrangement of devices in SI layer

To make the gravity center and stiffness center close, the bearings are located under every column, and the total yield force of the dampers is set to 3.9 % of the weight of the superstructure to give good performance. The arrangement of isolation devices in SI layer is shown in Figure 3.5. Dimensions and characteristics of the isolation devices are shown in Table 3.3. The characteristics of the building are summarized in Table 3.4. These devices were selected to support the vertical stress caused by the superstructure almost at the allowable pressure of each device. Following Table 2, the applicability of the equivalent linear analysis method is checked over as follows.

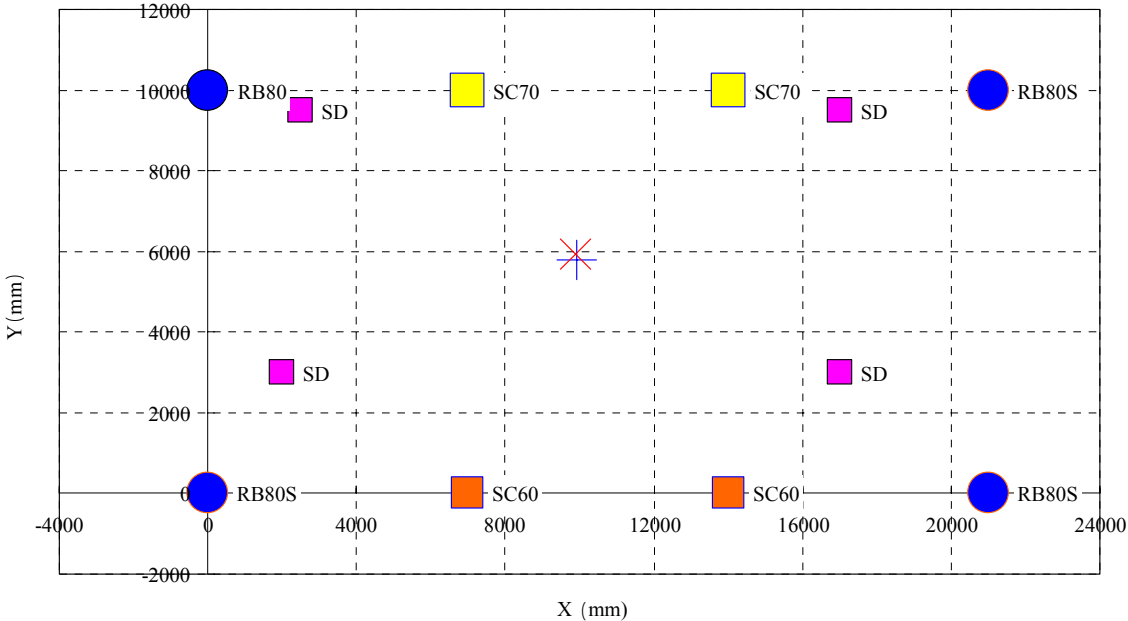


Figure 3.5 Arrangement of isolation devices in SI layer

Table 3.4 Characteristics of the building

M	2922.3 kN·s ² /m	K ₁	86460 kN/m
Q _y	926 kN	K ₂	4572 kN/m

3.3.1 Eccentricity ratio of SI layer

The maximum eccentricity ratio of SI layer under displacement of 500mm is 2.45%, which should be less than 3%. In Table 3.5, Eccentricity ratios of SI layer at each displacement are summarized. The maximum eccentricity ratio=2.45%<3%OK

Table 3.5 Eccentricity ratio of SI layer at each displacement

δ(mm)	50	100	200	300	400	500
Shear strain (%)	25	51	101	152	202	253
Eccentricity X(mm)	-35	14	71	104	126	141
Y(mm)	146	37	-91	-166	-216	-252
Eccentricity ratio X(%)	1.68	0.40	0.94	1.67	2.13	2.45
Y(%)	0.40	0.15	0.73	1.04	1.24	1.38

3.3.2 Total yield strength

The total yield strength of SI layer should be larger than 3% of the total weight upon the SI layer. If we assume each

footing has a weight of 50kN, the check procedure is as follows.

$$Q_y = 0.011 \times (5,161 + 4,659 + 3,767 + 3,728) + 184 \times 4 = 926 \text{ kN}$$

$$W = 28256 + \text{Footing weight} = 28256 + 50 \times 8 = 28656 \text{ kN}$$

$$Q_y/W = 926.5/28656 = 0.032 > 0.03 \quad \dots\dots\dots\text{OK}$$

3.3.3 Period of the isolation system considering only the stiffness of rubber bearings

Period of the isolation system considering only the stiffness of rubber bearings should be longer than 2.5 sec.

$$T_2 = 2\pi \sqrt{\frac{M}{K_t}} = 2 \times 3.14 \times \sqrt{\frac{28656/9.8}{4572}} = 5.02 > 2.5s \quad \dots\dots\dots\text{OK}$$

3.3. Setting of acceleration spectrum on the surface of the site

The acceleration spectrum on the surface of the site can be obtained by Equation (2). The design spectral acceleration at engineering bedrock ($V_s > 400\text{m/s}$) $S_d(T)$ defined in Equation (3) which is shown in Figure 1 for Level 2 input. The site amplification factor G_s is calculated based on the soil properties above engineering bedrock either by the simplified method according to the soil classification of first to third, or by the precise method calculated by using the wave propagation procedure considering the non-linearity of the soil profile. In Figure 3.6 are shown Site amplification coefficients for the three kind site classes. In this study, the precise method is used. In Table 3.6 is shown soil profile used in this study. The bottom of the base is at GL-4.0m. After several convergence calculations, the ground surface acceleration spectrum was obtained and shown in Figure 3.7.

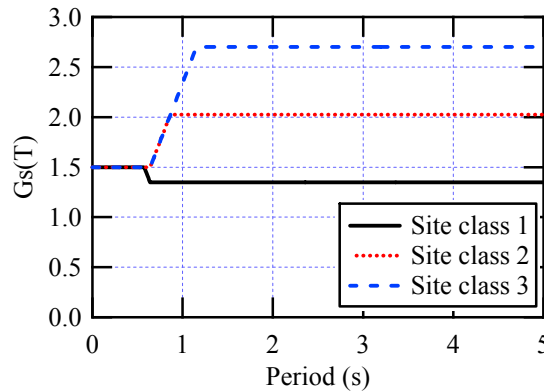


Figure 3.6 Site amplification coefficients for the three kind site classes (Japan)

Table 3.6 Soil profile used for this study.

Layer	Soil property	Depth(m)	N values	$V_s(\text{m/s})$	$\gamma(\text{t/m}^3)$
1	Clay	0.0	3	150	1.93
2	Clay	5.5	10	210	1.93
3	Clay	8.5	6	210	1.93
4	Sand	11.5	7	320	1.95
5	Sand	15.0	11	360	1.95
6	Sand	18.5	11	360	1.95
7	Sand	21.5	13	360	1.95
8	Sand	24.5	50	360	1.95
9	Clay	26.8	17	360	1.95
10	Sand	28.5	40	270	2.00
BED	Gravel	30.5	60	460	2.00

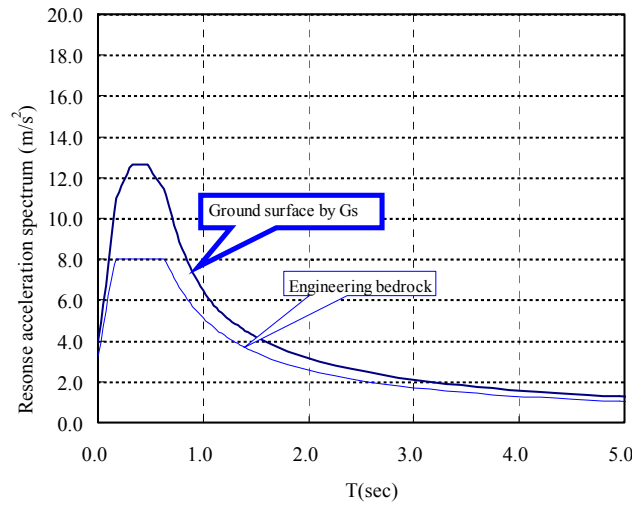


Figure 3.7 The ground surface acceleration spectrum.

3.5 Calculation of response displacement and shear-force of the SI layer

The SI layer in the ELM method is modeled as a normal bilinear model. The constants used for the building shown in section 3.1-3.4 are summarized in Table 3.7. Following the convergence procedure shown in Figure 2, the response displacement of the SI layer is obtained from the ground surface acceleration spectrum shown in Figure 3.7 and SI characteristics shown in Table 3.7. In Table 3.7, the iteration processes are shown too.

$$\delta = 0.396 \text{ m}$$

$$\delta_r = 1.1 \delta = 0.435 \text{ m}$$

$$\delta_r = \alpha \delta_r < \text{design displacement limit } {}_m\delta_d$$

α, γ are safety factors related with temperature dependent stiffness changes and property dispersions in manufacturing of devices. α is used to check the response displacement to be less than design displacement limit ${}_m\delta_d$ and secure the isolation gap. γ is used to gain safety for both super-structure and sub-structure. One may use $\alpha=1.2, \gamma=1.3$ defined in the building code or calculates the α, γ by considering the characteristics changes of the SI layer. As shown in Table 3.8, the characteristics changes include the changes to PLUS side (hardness) and MINUS side (softening). In table 3.9, the response results by the standard, PLUS change and MINUS change are shown.

Table 3.7 Iterative calculations to determine design displacement

Constants used in calculations							
M	2922.3 kN·s ² /m	K ₁	86460 kN/m				
Q _y	926 kN	K ₂	4572 kN/m				
Iterative Calculations		Iter 1	Iter 2	Iter 3	Iter 4	Iter 5	Converged
δ (m)	$\frac{M F_h(h, T_e) S_a(T_e)}{K_e}$	0.416	0.412	0.408	0.404	0.400	0.396
K _e (kN/m)	$\frac{Q_y + K_2 \delta}{\delta}$	6468	6500	6538	6572	6612	6649
h _d		0.179	0.181	0.184	0.185	0.188	0.190
F _h	$\frac{1.5}{1 + 10(h_v + 0.8h_d)}$	0.617	0.613	0.608	0.604	0.600	0.595
T _D (s)	$2\pi \sqrt{\frac{M}{K_e}}$	4.223	4.213	4.201	4.190	4.177	4.165
S _a (T _e)	G _s 5.12 / T	0.920	0.916	0.912	0.908	0.904	0.900

Table 3.8 the characteristics changes to PLUS side (hardness) and MINUS side (softening).

Parameters	standard		+ changes		- changes	
Rubber bearings						
$\Sigma nK1(kN/m)$	4060		32%	5359	-18%	3329
Stiffness K1	Aging (%)		10%		0%	
	Temperature (%)		7%		-3%	
	Dispersion (%)		15%		-15%	
Slider with Elastomer						
$\Sigma nK1(kN/m)$	52000		57%	81640	-34%	34320
$\Sigma Qy(kN)$	190		15%	219.0	5%	200.0
Stiffness K1	Aging (%)		20%		0%	
	Temperature (%)		20%		-4%	
	Dispersion (%)		20%		-20%	
	Vertical load (%)		10%		0%	
Yield load Qy	Aging (%)		0%		0%	
	Temperature (%)		0%		0%	
	Dispersion (%)		20%		-20%	
	Vertical load (%)		65%		25%	
Steel dampers						
$\Sigma nK1(kN/m)$	30400		15%	34960	-15%	25840
$\Sigma nK2(kN/m)$	512		0%	512	0%	512
$\Sigma nQy(kN)$	736		16%	853.76	-14%	632.96
Stiffness K1	Aging (%)		0%		0%	
	Temperature (%)		0%		0%	
	Dispersion (%)		10%		-10%	
Stiffness K2	Aging (%)		0%		0%	
	Temperature (%)		0%		0%	
	Dispersion (%)		10%		-10%	
Yield load Qy	Aging (%)		0%		0%	
	Temperature (%)		1%		-2%	
	Dispersion (%)		10%		-10%	
Total						
$\Sigma nK1(kN/m)$	86460		+41%	121959	-27%	63489
$\Sigma nK2(kN/m)$	4572		+28%	5871	-16%	3841
$\Sigma nQy(kN)$	926		+16%	1073	-10%	833

Table 3.9 Response results for standard, PLUS change and MINUS change parameters.

Parameters		standard	+ changes	- changes
Unloading stiffness	K_1 (kN/m)	86460	121959	63489
Post yield stiffness	K_2 (kN/m)	4572	5871	3841
Yield load	Q_y (kN)	926	1073	833
Amplification factor of acceleration	G_s	1.230	1.230	1.230
Equivalent viscous damping factor	h_d	0.190	0.194	0.190
Reduction ratio	F_h	0.595	0.587	0.595
Shear-force of SI layer	Q (kN)	2631	2961	2404
Standard displacement	δ (m)	0.396	0.342	0.433
Response displacement of SI layer	δ_r (m)	0.435	0.376	0.476
Max. horizontal clearance (No passerby)	(m)			0.576
Max. horizontal clearance(Inspection)	(m)			0.676
Max. horizontal clearance (Passerby)	(m)			1.276
Shear-force of hysteretic dampers	Q_h (kN)	1117	1235	
Shear-force of isolators and restorers	Q_e (kN)	1606	1832	
Seismic force subjected to SI layer	Q_{iso} (kN)	2723	3067	
Coefficient of shear-force of SI layer	C_{ri}	0.095	0.107	
Coefficient shear-force of superstructure	C_{ri}	0.099	0.111	
Safety factor	γ		1.13	
Shear force ratio for dampers ≥ 0.03	μ	0.039		
Tangent stiffness at standard displacement	K_t (kN/m)	4572		
Tangent Period $T_t \geq 2.5$	T_t (s)	5.023		

3.6 Calculation of shear-force of superstructure and substructure

The response results are summarized in Table 3.9. The detailed procedure is as follows.

3.6.1 SI layer

$$C_{ri} = \gamma \frac{\sqrt{(Q_h + Q_e)^2 + 2\varepsilon(Q_h + Q_e)Q_v + Q_v^2}}{Mg} \frac{A_i(Q_h + Q_v) + Q_e}{Q_h + Q_v + Q_e} = \gamma \frac{A_i Q_h + Q_e}{Mg}$$

$$Q_{iso} = \gamma \sqrt{(Q_h + Q_e)^2 + 2\varepsilon(Q_h + Q_e)Q_v + Q_v^2} = \gamma(Q_h + Q_e) = 3067$$

The calculated A_i and C_{ri} are summarized in Table 3.10.

3.6.2 Super-structure

The response shear force is shown in Table 3.10 and Figure 3.8 comparing with the design shear force.

Table 3.10 Response results of super-structure and design values.

	Height m	Weight kN	Ai	Cri	Qi kN	O·T·M kN·m	Design			
							Coef. Cix	Cix/Cri	Qi kN	O·T·M kN·m
7	3.20	2854	2.155	0.158	450	1440	0.240	1.522	685	2192
6	3.00	3328	1.728	0.139	859	4016	0.220	1.584	1360	6272
5	3.00	3293	1.528	0.130	1233	7714	0.200	1.537	1895	11957
4	3.00	3331	1.392	0.124	1590	12484	0.180	1.450	2305	18872
3	3.00	3379	1.284	0.119	1933	18282	0.160	1.340	2590	26641
2	3.00	3390	1.193	0.115	2260	25061	0.140	1.213	2741	34863
1	3.80	4220	1.094	0.111	2643	35106	0.130	1.170	3093	46617
SI	1.50	4461	1.008	0.107	3032	39654	0.120	1.118	3391	--

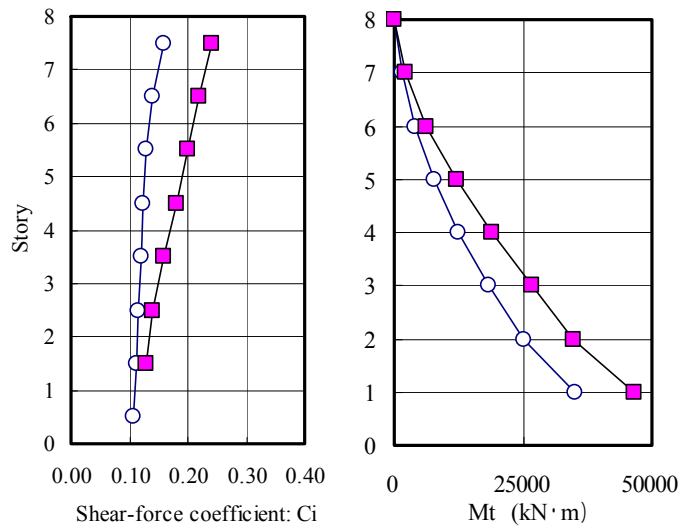


Figure 3.8 Comparison with calculated and design values of Ci and O·T·M.

3.6.3 Story drift of super-structure and vertical load changes on isolator devices due to the horizontal earthquake load.

The story drift of super-structure and vertical load changes on isolator devices due to the horizontal earthquake load are obtained by applying the earthquake force shown in Table 3.10 horizontally to the super-structure statically. In Figure 3.9 is shown the analytical model. The base at each isolator device can be modeled as fixed or supported by a spring with the value of vertical stiffness. The design shear force is used to give safety other than calculated Qi. The drift angle in all floors of the super-structure must be less than 1/300 demanded by the building code. The vertical load changes are used to check the maximum and minimum pressure on each isolator device shown in section 3.8.

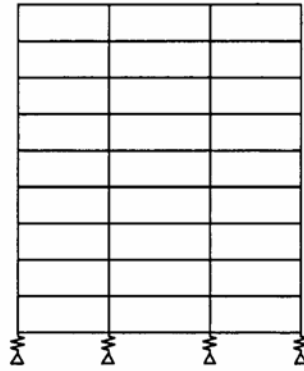


Figure 3.9 The analytical model to calculate drift angle and vertical load changes.

3.6.4 Sub-structure

The foundation is assumed at depth 4m underground. The shear force of the sub-structure can be obtained by following step.

$$Q_{sub} = Q_{iso} + 2 k W_b = 3067 + 2 * 0.09 * 6000 = 4147 \text{ kN}$$

k: seismic intensity for sub-structure. $k = 0.1(1 - H/40) = 0.09$

W_b : weight of the foundation. $W_b = 6000 \text{ kN}$.

3.7 Evaluation of response values of SI layer from wind load

The wind load is confirmed by two levels, where the return period is 50 and 500 years, respectively. The response is related with the geometry of the building and wind velocity. In Figure 3.10 is shown the response displacement of the SI layer. The designer should take care not to let the SI layer has large deformation even during extreme wind. In Figure 3.11, is shown the comparison between two level's wind loads and design shear force. Since this building is small, the design shear force is large enough.

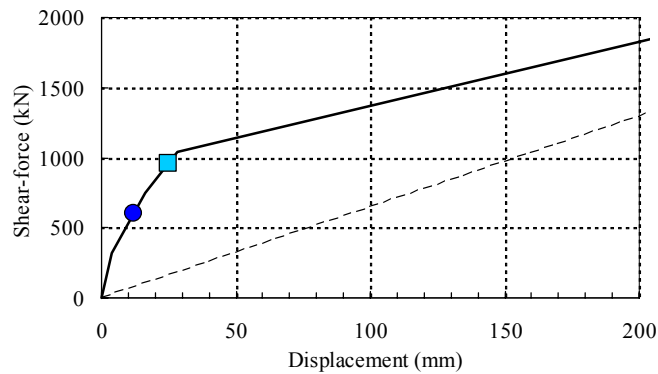


Figure 3.10 Response against wind load on the force-displacement curve of SI layer

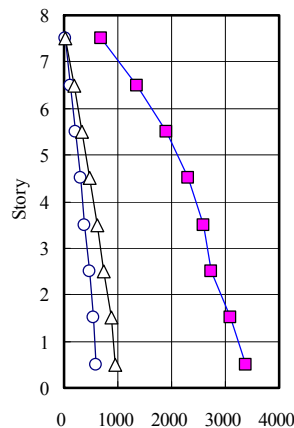


Figure 3.11 Comparison between two level's wind loads and design shear force.

3.8 Confirmation of safety of devices for vertical load

The vertical load changes on isolator devices due to the horizontal earthquake load were calculated at section 3.6.3. A vertical earthquake load of 0.3g is also applied to check maximum and minimum pressure on each isolator device. The maximum response displacement of 0.476m due to MINUS change is used.

Maximum pressure: $W_D \cdot 1.3 + V_{seis}$

Minimum pressure: $W_D \cdot 0.7 - V_{seis}$

W_D : vertical loads on isolation devices shown in Table 3.2

V_{seis} : vertical load changes calculated at section 3.6.3

In Table 3.11, is shown an example of the maximum and minimum pressure check on the RB80. In Figure 3.12, are shown two cases of vertical load for isolator devices. Case 1 shows permanent load at displacement zero. Case 2 shows the above maximum and minimum pressure on each isolator device.

Table 3.11 Maximum and minimum pressure check on the RB80.

Devices (isolator)	Vertical load W_D (kN)	Seismic load (V_{seis})		$W_D \cdot 1.3 + V_{seis}$		$W_D \cdot 0.7 - V_{seis}$	
		X (kN)	Y (kN)	X (kN)	Y (kN)	X (kN)	Y (kN)
RB80	4363	1135	736	6807	6408	1919	2318

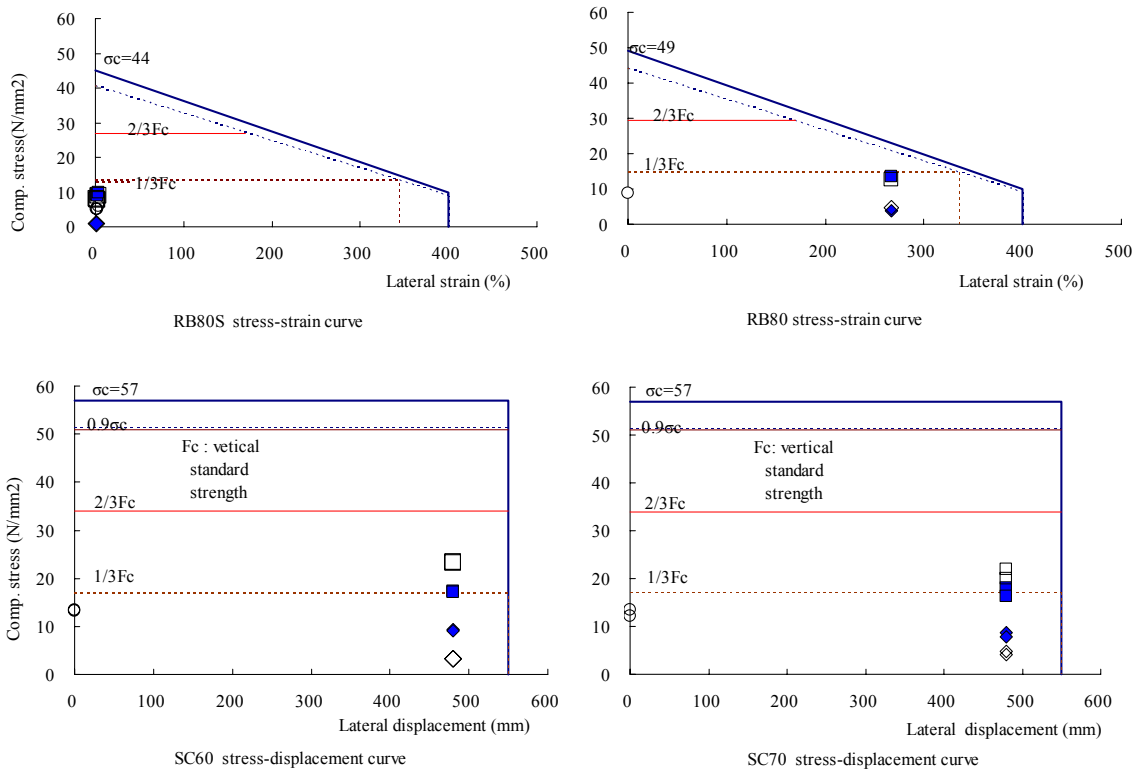


Figure 3.12 Comparison between response and limit of isolator devices.

3.9 Securing safety of connections of devices to structures

The footings and beams must be strong enough to ensure the isolator or damper devices work normally during an earthquake. To design those structure elements and the connection plates or anchor plates, the extreme deformation of the SI layer is assumed. The connection part is acted with a shear force and large moment as shown in Figure 3.13 and calculated by following equations. The maximum shear force and moment check on the RB80 is shown in Table 3.12. Fixing bolts and anchor stud bars etc. should be designed using these values too.

$$N_d = W_D \cdot 1.3 + V_{seis}$$

$$\delta = \delta_r$$

$$Q_d = Q_y + K_2 \delta$$

$$M = M_v + tM_d = 1/2 N_d \delta + Q_d(h_t + 1/2 h)$$

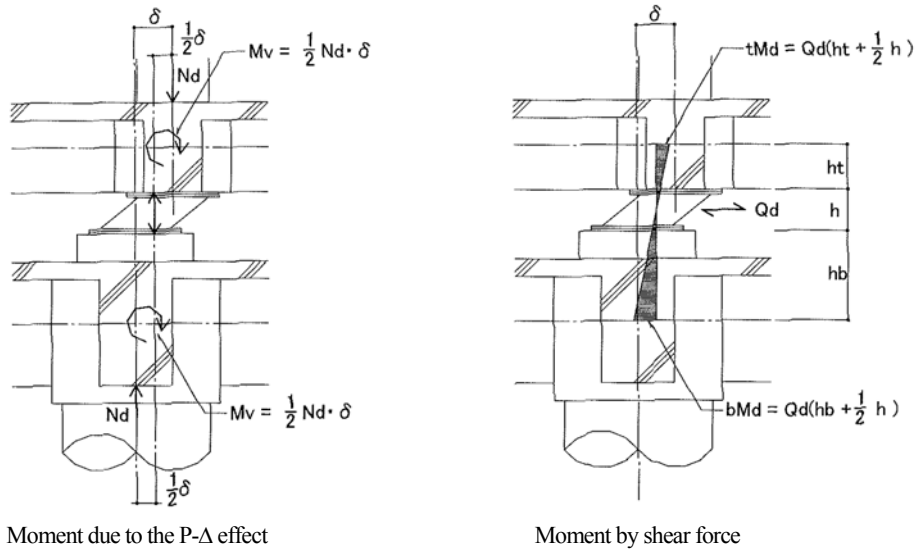


Figure 3.13 Moment acting on the footings and beams.

Table 3.12 Maximum shear force and moment check on the RB80.

	N_d (kN)	δ (m)	Q_d (kN)	M_v (kN m)	h (m)	h_t (m)	tM_d (kN m)	M (kN m)
RB80	6807	0.476	519	1620	0.5	0.6	441	2061

3.10 Confirmation of satisfaction of stipulations on SI system

The clearance around the SI building should be maintained. As shown in Table 3.9, the maximum response displacement of SI layer is 0.476m. Then the clearance for inspection should be 0.676m, the clearance for passerby should be 1.276m.

4. CONCLUSIONS

The flow-chart to design a seismically isolated building basing on the equivalent linear method (ELM) was introduced. The design procedure was demonstrated in detail by design a seven-story RC building. If one change the earthquake input into the local one, one can design using this procedure too.

5. REFERENCE

- MRIT, etc., 2000, *The Notification and Commentary on the Structural Calculation Procedures for Building with Seismic Isolation –2000–* (in Japanese).
Higashino, M., S. Okamoto, 2006, *Response Control and Seismic Isolation of Buildings*, Taylor & Francis
ISO 22762, 2005(E)