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# SEISMIC DESIGN PROVISIONS OF BUILDINGS IN JAPAN

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**ABSTRACT :** With the experience gained from some major earthquakes, Japan in a major development revised the Building Standard Law and proposed a Two-Phase Design Method for earthquakes in 1981. The first- and second-phase designs are for withstanding moderate and severe earthquakes respectively. In the first-phase design, chief revision of seismic force is proposed. The newly introduced second-phase design is for several checking, including story deformation angle, rigidity and eccentricity, horizontal load carrying capacity of the buildings, which have been initially designed by the first-phase design. The scope of these designs is limited to the buildings not higher than 60*m*. The structural design of the buildings which exceed that limit or in other words the highrise buildings, are designed based on the time story earthquake response analysis through fulfilling a set of criteria. The overall and highrise constructions in Japan, and the development of the seismic design standard with major earthquake events are also discussed.

**KEY WORDS :** construction type, two-phase design, seismic force, story drift, rigidity, eccentricity, ultimate strength capacity, specifications, design mechanism, response analysis

## INTRODUCTION

Japan, a country believed to be seismically very active. There are about two thousand active faults in Japan, more than in most other countries. Most parts of Japan are susceptible to strong earthquakes of magnitude 7 or more on the Richter scale, and many of the quakes may occur near large cities (Matsuda 1981). All buildings must be earthquake resistant with proper planning and structural design. The earthquake resistance design, methods of earthquake resistance calculation, structural requirements, and construction methods had been developed and/or changed in this century, especially after the great Kanto Earthquake of 1923, and the experiences gained and lessons learned from subsequent major earthquakes occurred in the other parts of Japan.

Major development was achieved in 1981 by the introduction of two-phase design (first-phase design and second-phase design) method. The first-phase design is for withstand with almost no damage against moderate earthquake motions, which would occur several times during the life time of a building, and the second-phase design is for not collapse nor harm human lives by the severe earthquake motions, which would occur less than once during the life time of a building.

This paper basically describes the current seismic design provisions of buildings in Japan. However, the overall and highrise construction in Japan, and the change of the provisions with major earthquake events are also presented.

This paper has been written with the aim of introducing building design provisions in Japan to the professional engineers in Bangladesh

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so that they can make use of the contents by easy access to this document.

## CONSTRUCTION IN JAPAN

### Overall Construction

Figure 1 shows the percentage of overall constructions of houses and buildings in Japan, distinguished according to the material used for the construction, regardless of the number of stories. This data is based on the total volume of construction carried out in the span of ten years from 1985 to 1994. The lion share belongs to the material, timber. But the timber construction is very common up to two stories Japanese traditional house, as can be seen from Fig.2, which shows the types of constructions in terms of stories. Timber houses of one story are less common and three story are few in number. Concrete block masonry apartments are scarce (Fig.1).

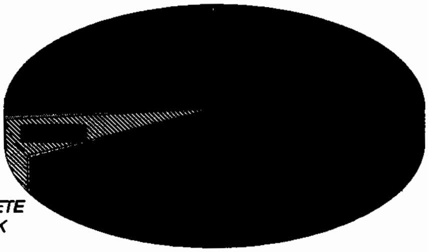



*Fig 1. Percentage of Overall Constructions (from 1985 to 1994)*

Reinforced concrete (RC) buildings are very common from two to five story, which are usually constructed by using reinforced concrete wall structures, and used for apartment houses. Reinforced concrete buildings from six to nine stories are less common. They are basically RC frame structures with or without shear walls. RC buildings up to 45 story are constructed or under construction, but they are very few in number. These buildings usually consist of RC frame only. Shear walls in longitudinal or transverse directions are usually not used to avoid complexity in analysis, design and construction.

Composite steel reinforced concrete structures (SRC) from five to fifteen stories are common. SRC buildings up to 40 story and so are presently constructed, but they are very few in number. Steel structures (STEEL) are very popular because of their rapid erection method in the construction sites. Therefore, up to two or five stories buildings are very common or less common. The tallest building, at present in Japan is the 70 story Landmark Tower at Yokohama MM21, an abbreviation for frame buildings after research and development on RC structures. And currently, even a 45 story RC building is under construction. A five-year-project from 1988 to 1993 for "the Development of Advanced Reinforced

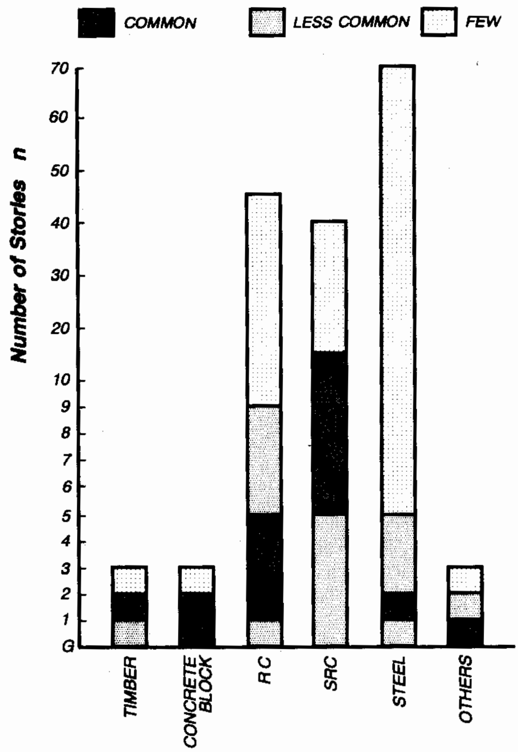



*Fig 2. Types of Construction in Terms of Number of Stories*

Minato Mirai 21 means Future Port of 21st Century, has been constructed by steel structures. The area "others" include the mixture of two or more materials used in the construction. They are also scarce like concrete block masonry.

**Highrise Construction**

Figure 3 shows the amount of annual highrise constructions in Japan in the span of twenty years from 1974 to 1993. Buildings taller than 60*m* in height are subjected to the review of the Structural Review Committee for Highrise Buildings of the Building Center of Japan. The data shown in this figure are the amount of reception by the Building Center from the designer in the case of the buildings or some other structures, for instance, tower/chimney, which are taller than 60*m* in height. Such structures other than buildings are very few in number.

As can be seen from the figure, steel structures are contributing to the major parts of highrise construction. The steel related constructions are carried out by steel structures (STEEL), composite steel and reinforced concrete structures (SRC), composite steel with reinforced concrete and steel structures (SRC+STEEL). The basements, and in some cases the neighbouring stories above ground level of the buildings with steel structures, are usually constructed by SRC and/or RC.

Until early 1970s, the height of reinforced concrete (RC) buildings had been limited to about 20*m* in practice due to peoples confusion regarding the seismic resistance of concrete structures because of the bitter experience gained from the 1923 Kanto Earthquake. But some leading Construction Co. approached to the construction of highrise RC Concrete Buildings Using High-Strength Concrete and Reinforcement", usually known as "New RC Project" was organized by the Ministry of Construction, Japanese Government. This will probably lead to the construction of RC buildings up to the height of 200*m*. The area "others" basically include the structures consist of concrete-filled tubular column and so.

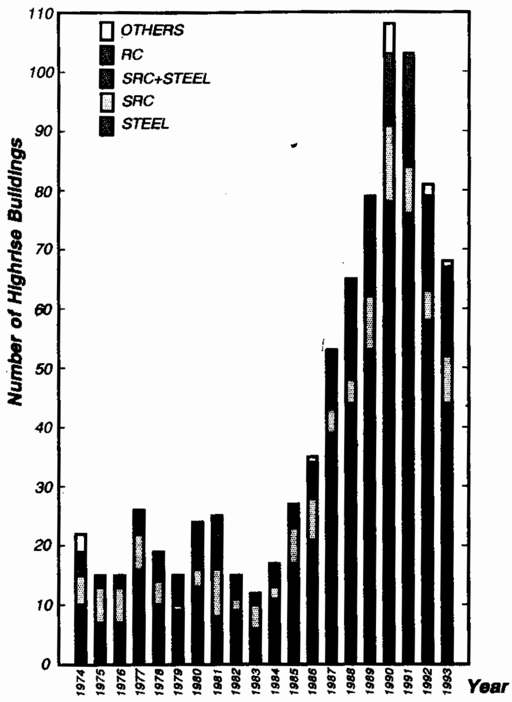


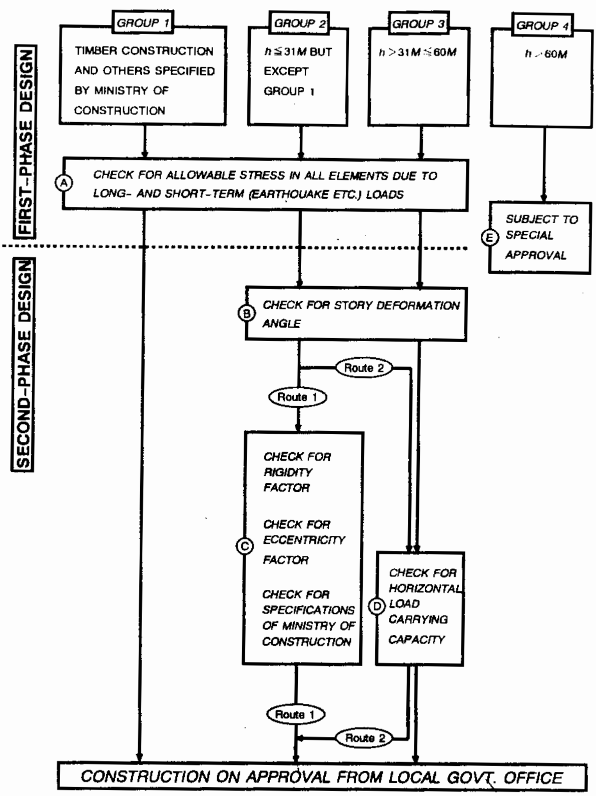

*Fig 3. Highrise Construction (from 1974 to 1993)*

## DEVELOPMENT OF SEISMIC DESIGN IN JAPAN

An official announcement of Urban Building Law of Japan was made in 1920, but seismic design provision was introduced in 1924 when the Urban Building Law had been revised as a consequence of the great Kanto Earthquake of 1923 (Table 1). This introduction first incorporated a seismic coefficient of 0.1. The seismic coefficient was raised to 0.2, and indication was made that in the design procedure the long- and short-term load should be specified separately in Japan Building Standard 3001 published in 1947 by the Ministry of Construction as a further development. In 1950, the Urban Building Law was replaced by Building Standard Law of Japan, in which the seismic coefficient 0.2 was limited up to 16*m* height and gradual increase of the coefficient above that height was prescribed. Also, indication was made for some specific parts of buildings, for instance, penthouse, that should be designed by using the seismic coefficient 0.3.

The restriction on the limitation of height 31*m*, had been abolished in 1963 by the revision of Building Standard Law, and technical guidance on highrise buildings was published by Architectural Institute of Japan (AIJ) in 1964.

In 1968, the Tokachi Oki Earthquake occurred, which claimed not so large number of lives but caused severe damage to fifteen percent of code-designed reinforced concrete buildings and some other structural




Note: *h* is the total height

*Fig 4. Flowchart of Seismic Design*

**Table 1 Major Earthquakes, and Development of Building Design Standard**

| Year | Major Earthquakes | Year | Dev. of Building Design Standard |
|---|---|---|---|
| | | 1920 | Announcement of Urban Building Law (UBL) |
| 1923 | Great Kanto Earthquake (M7.9) Persons Killed: 142807 House Damaged: 128266 | 1924 | Revised the UBL, Introduction of Seismic Coefficient 0.1 |
| 1946 | Nankaido Earthquake (M8.0) Persons Killed : 1330 Houses Damaged: 9060 | 1947 | Seimic Coefficient Increased to 0.2, Long- and Short-term Loads Distinguished |
| 1948 | Fukui Earthquake (M6.28) Persons Killed : 3895 Houses Damaged : 35420 | 1950 | Building Standard Law (BSL) Replaced UBL, Seismic Coefficient above 16m Increased with Height, and in Soft Subsoil Area 0.3 |
| | | 1963 | BSL Revised, Height Limitation Abolished |
| 1964 | Niigata Earthquake (M7.5) Persons Killed : 26 Houses Damaged :1960 | 1964 | Guideline on Highrise Building by AIJ |
| 1968 | Tokachi Oki Earthquake (M7.9) Persons Kiled : 52 Houses Damaged : 673 | 1971 | BSL Revised, Introduction of Ultimate Strength Design in Shear of RC Buildings |
| 1975 | Oitaken Chubu Earthquake (M6.7) Persons Killed : 0 Houses Damaged : 58 | 1977 | Proposal for New Seismic Design Method |
| 1978 | Miyagiken Oki Earthquake (M7.4) Persons Killed : 28 Houses Damaged : 1183 | 1981 | Published New Seismic Design Method (Two-Phase Design Method) |
| 1983 | Nihonkai Chubu Earthquake (M7.7) Persons Killed : 104 Houses Damaged : 934 | 1988 | Design Guideline for Earthquake Resistant RC Buildings Based on Ultimate Strength Concept (Draft) by AIJ |
| 1995 | Hyogoken Nanbu Earthquake (M7.2) Persons Killed : 5472 Houses Damaged : 81972 | | |

buildings. In consequence of this earthquake, partial revision of the Building Standard Law, and introduction of ultimate strength design in shear of reinforced concrete by AIJ were made in 1971. Furthermore, a five-year-project from 1972 to 1977 was conducted by the Ministry of Construction, in the aim of establishment of a new seismic design method. The ductility of members was especially addressed in this project after learning lessons from the 1968 earthquake. The Ministry of Construction released the proposal in 1977. In the same year, the Japan Association for Building Disaster Prevention published a review procedure of existing building for seismic safety.

In the following year, the Miyagiken Oki Earthquake occurred. Many buildings suffered severe damage due to torsional effect demonstrating more complicated characteristics of urban disaster. The similar type of damage was observed in the 1975 Oitaken Chubu Earthquake. The Miyagiken Oki Earthquake was one of the most conspicuous event and so it was a great concern to the Ministry of Construction and the other authorities. The lessons learned from this earthquake enabled to revise and establish the so called New Seismic Design Method with the introduction of Two-Phase Design Method through the Enforcement Order of Building Standard Law in 1981. This new seismic design method is currently followed in the design of buildings in Japan. Guidelines to Structural Calculation Based on the Revised Building Standard Law had been published by the Building Center of Japan by the assistance of Housing Bureau and Building Research Institute, Ministry of Construction (Housing Bureau and Building Research Institute, Ministry of Construction 1981). This paper is prepared by following this document along with Aoyama (1981).

In 1984, "Recommendation for Seismic Design of Building Foundation" was published by Building Center of Japan, and in 1988, "Recommendation for Design of Building Foundation" was published by AIJ. A draft on "Design Guideline for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept" was published by AIJ in 1988. In 1991, a guideline for check and repair of damaged buildings was published by the Japan Building Disaster Prevention Association.

The very recent earthquake, the Hyogoken Nanbu Earthquake occurred on January 17th, 1995, which claimed about 6,000 lives and damaged about 82,000 houses and buildings. First evidence suggested that those buildings built after the introduction of the new earthquake code in 1981, have survived the earthquake without any or major structural damage. However many older structures have suffered significant damage. This earthquake occurred very close to the city of Kobe and the strength of shaking was exceptionally strong. Therefore, Japan experienced the destruction of this scale in an urban area since the great Kanto Earthquake of 1923.

## SEISMIC DESIGN PROVISIONS

### Flow of Structural Design

The design flow outlined in the New Seismic Design Method is shown in Fig.4. Two-phase design, namely first-phase design and second-phase design, is introduced in the new proposal. All buildings are divided into four groups. Group 1 includes houses constructed by timber, and the other buildings, which do not require second-phase design, specified by the Ministry of Construction. Group 2 through 4 are divided distinctly based on the height of the buildings.

The buildings belong to Group 1 through 3 are usually designed by following the specifications and guidance recommended by the Ministry of Construction. The buildings belonging to Group 4 are designed by earthquake response analysis fulfilling some earthquake resistant design criteria. These buildings are subjected to the review of the Structural Review Committee for Highrise Buildings of the Building Center of Japan. Then an approval from the Ministry of Construction is issued for structural design and construction.

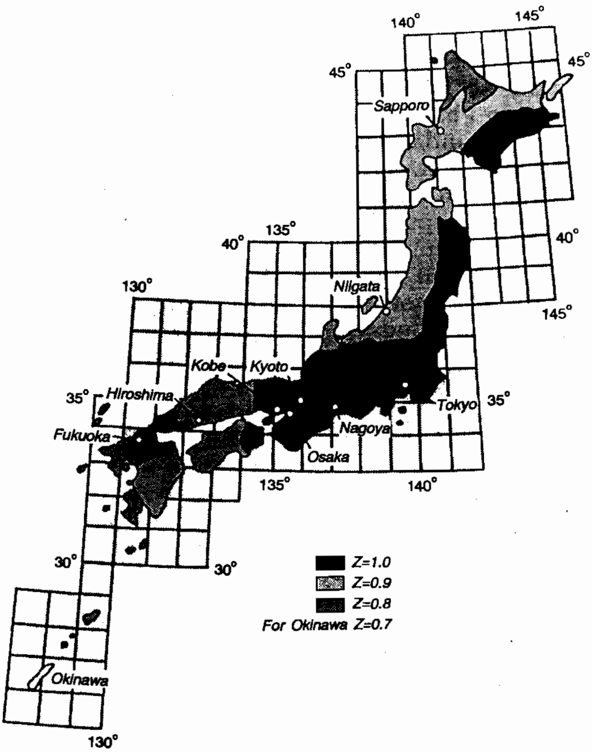



*Fig 5. Seismic Hazard Zoning Coefficient*

The buildings in Group 1 through 3 are first subjected to the first-phase design or in other words the conventional design through the checking for allowable stress in all members due to long- and short-term loading, as shown in [A]. The short-term loading obviously include the seismic loading and so. Group 2 and 3 require to go through the second-phase design, which is not required for Group 1. Both Group 2 and 3 enter second-phase design demanding check for story deformation angle, as shown in [B]. Thereafter, Group 2 may follow either Route 1 entering [C] or Route 2 entering [D], a judgement is made by experienced engineer.

If Route 1 is followed, the checking for rigidity factor, eccentricity factor, and specifications of the Ministry of Construction is required, as shown in [C]. These checkings may be avoided if Route 2 is followed by checking for horizontal load carrying capacity, as shown in [D]. Group 3 directly approaches from [B] to [D] for checking the horizontal load carrying capacity. The buildings in Group 4 are subjected to special approval.

**First-phase Design ([A] of Fig.4)**

The first-phase design, basically the conventional design, requires to check for allowable stress in all elements. Therefore, the design is based on working stress design method. The purpose of this design is to protect buildings with almost no damage in the case of moderate earthquakes which may occur several times during the lifetime of the buildings. For structural calculations, the procedure adopted by the designer in practice is to (a) assume sectional properties of all members and joints, (b) estimate member stiffness for modeling frame structure, (c) calculate permanent and temporary loads, and the resulting stress in every members (d) calculate stress in every section resulting from stress in member, and (e) check for the sectional stress whether exceed the allowable stress of the materials that would be used for construction.

Load Combinations : For permanent or long-term loading, the following load combinations are recommended.

$D + L$

$D + L + S$ *in snowy area*

For temporary or short-term loading, the following load combinations are recommended.

$D + L + S$ *in snowy area*

$D + L + W$

$D + L + W + S$ *in snowy area*

$D + L + E$

$D + L + E + S$ *in snowy area*

where, $D$, $L$, $S$, $W$, and $E$ stand for dead, live, snow, wind and earthquake respectively. In case of temporary loading, the combination associated with earthquake loading usually govern the design.

Lateral Static Earthquake Force above Ground Level : The New Seismic Design Method mainly revised the method of evaluation of the minimum lateral seismic shear $Q_i$ of $i$-th story above the ground level. The $Q_i$ shall be determined in accordance with the following equations.

$$Q_i = C_i \bullet \sum_{i=1}^{n} W_i \quad (1)$$

$$C_i = Z R_t A_i C_o \quad (2)$$

where, $W_i$ : weight of building above $i$-th story (this includes dead load, reduced live load, and snow load in snowy area); $n$ : number of stories; $C_i$ : lateral seismic shear coefficient of the $i$-th story; $Z$ : seismic hazard zoning coefficient as shown in Fig.5 (if seismic activity at a construction site is not investigated, the seismic hazard zoning coefficient $Z$ should be unity); $R_t$ : factor representing dynamic characteristics of a structure, which shall be determined by the type of soil profile and the fundamental natural period of the building; $A_i$: lateral shear distribution factor in vertical plane, which shall be determined by the fundamental natural period and the weight distribution of the building; $C_o$: standard shear coefficient, which shall be not less than 0.2 (0.3 for wooden building in soft subsoil area) for the first-phase design and 1.0 for the second-phase design. The vibration characteristics factor $R_t$ is extrapolated from the following empirical expressions for three types of soil.

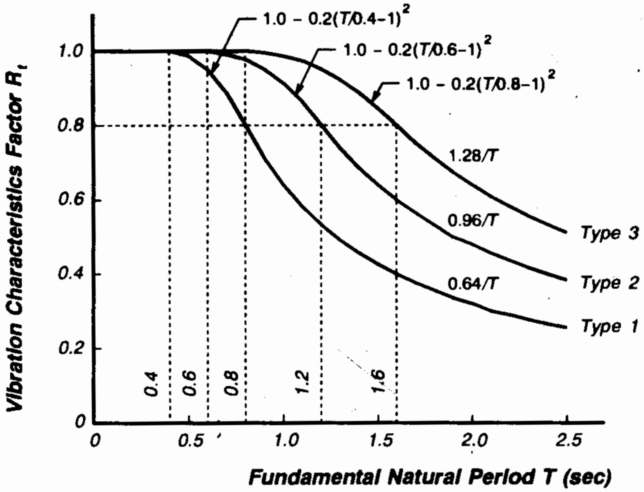



*Fig 6. Fundamental Natural Period-Vibration Characteristics Factor*

$$R_t = 1.0 \qquad \text{for } T < T_c$$
$$R_t = 1.0 - 0.2\,(T/T_c - 1)^2 \qquad \text{for } T_c \le T < 2T_c \qquad (3)$$
$$R_t = 1.6\,(T_c/T) \qquad \text{for } 2T_c \le T$$

where, $T$ : fundamental natural period of structure; $T_C$ : critical period of subsoil (0.4 *sec* for Type 1 soil composed of rock, stiff sand and gravel, 0.6 *sec* for Type 2 soil composed of others, and 0.8 *sec* for Type 3 soil composed of alluvium). The fundamental natural period $T$ is to be calculated from the following empirical expression.

$$T = h\,(0.02 + 0.01\alpha) \qquad (4)$$

where, $h$ : height of the building in *meter*; $\alpha$ : the ratio of the height of stories, which consist of steel columns and beams, to the total height $h$. This is a very handy calculation method of $T$, but in many cases $T$ is determined from the stiffness calculation. Therefore, for reinforced concrete structures $T = 0.02h$, and for steel structures $T = 0.03h$. The resulting value of $R_t$ is shown in Fig.6. The lateral shear distribution factor $A_i$ is extrapolated from the following empirical expression.

$$A_i = 1 + [1/(\alpha_i)^{1/2} - \alpha_i]\,[2T/(1+3T)\,] \qquad (5)$$

$$\alpha_i = \sum_{i=i}^{n} W_i + \sum_{i=1}^{n} W_i \qquad (6)$$

Lateral Static Earthquake Force in the Basement Stories : The lateral seismic shear in basement $Q_B$ shall be determined in accordance with the following equation.

$$Q_B = Q_p + k\,W_B \qquad (7)$$

where, $Q_p$ : portion of the seismic story shear force in the adjacent upper story that is carried by columns and shear walls above the basement being considered; $k$ : seismic design coefficient of the basement as determined in accordance with Eq.(8); $W_B$ : weight of the basement due to dead and live loads in the story being considered. The seismic design coefficient of basement $k$ shall be determined in accordance with the following expression.

$$k \geq 0.1\,(1 - H/40)\,Z \qquad (8)$$

where, $H$ : depth of the basement from ground level in *meter* (if the depth exceeds 20*m*, it should be taken 20*m*). Figure 7 shows a building with basement story and the distribution of seismic design coefficient *k*.

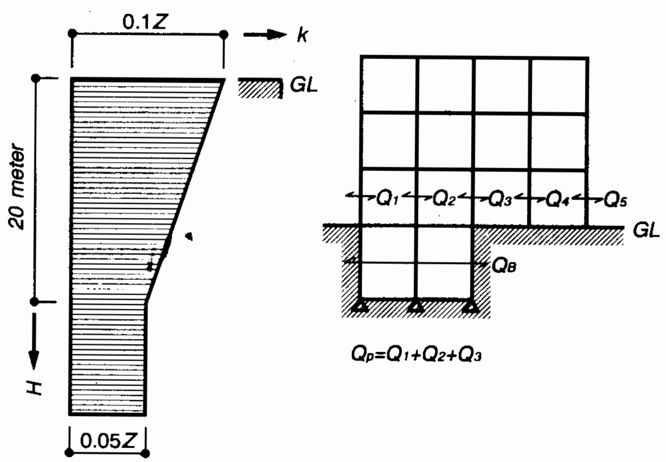



*Fig 7. Distribution of Seismic Design Coefficient in Basement Stories*

Lateral Static Earthquake Force on Appendages : The lateral seismic shear of penthouse, chimney, tower, cistern, parapet and other appendages on buildings $q$ shall be determined in accordance with the following equation.

$$q = k_a\,w \qquad (9)$$

where, $k_a$ : seismic design coefficient of appendages (it shall be greater than 1.0, but the value can be minimized down to 0.5 in case no harm will occur); $w$ : the weight of the appendage.

Buildings Not Subjected to Second-phase Design : The buildings in Group 1 of Fig.4 with the following specifications prescribed by the Ministry of Construction are subjected to the first-phase design only, that means the second-phase design is not necessary for them.

(1) Masonry and reinforced concrete block masonry buildings : Number of story $n \leq 3$ (excluding the basement).

(2) RC or SRC buildings : (a) total height $h \leq 20m$; (b) the following empirical equations must be satisfied for every story.

$$\Sigma 250A_w + \Sigma 70A_c \geq Z\,W\,A_i \qquad \textit{for RC} \quad (10a)$$
$$\Sigma 250A_w + \Sigma 100A_c \geq Z\,W\,A_i \qquad \textit{for SRC} \quad (10b)$$

where, $A_w$ : area of shear walls in the direction being considered in $cm^2$; $A_c$ : area of columns in $cm^2$; $W$ : weight of the portion of the building being considered in *Newton* ($N$). The empirical Eq.(10) is converted from $kgf$ to $N$ by approximating 1 $kgf$ = 10 $N$.

(3) Steel buildings : (a) number of story $n \leq 3$ (excluding the basement); (b) total height $h \leq 13m$ and eaves height $\leq 9m$; (c) span length $\leq 6m$; (d) total floor area $A_f \leq 500m^2$; (e) standard shear coefficient $C_0$ used in the first-phase design $\geq 0.3$; (f) end connections and joints of braces which resist horizontal forces must not fracture when the braces yield.

(4) Buildings consisting mixture of two or more of timber, masonry, reinforced concrete masonry and steel structures, or mixture of one or more of them with RC or SRC : The same specifications of (a), (b), (d) of steel buildings when steel is not concerned, (a) through (f) of steel buildings and (b) of RC or SRC buildings when steel is concerned.

(5) Prefabricated industrial houses approved by the Ministry of Construction.

(6) Other than (1) through (5) those possessing greater safety against earthquake in comparison to the buildings belonging to (1) through (5).

## Second-phase Design

The newly added second-phase design could be achieved through the lessons learned especially from the Tokachi Oki Earthquake of 1968, the Miyagiken Oki Earthquake of 1978, and the Oita-ken Earthquake of 1975. They revealed that the regular shape buildings responded very nicely but the performance of the irregular buildings was either not satisfactory or resulted into severe damage and collapse of the structures. The vulnerability of the irregular buildings gave a great momentum to the concerned authorities, and therefore the necessity of second-phase design came into action. In case of buildings of Group 2 in Fig. 4, experienced designers make judgement whether to adopt Route 1 or Route 2. Usually, Route 1 is adopted for regular shape buildings and Route 2 is adopted for irregular shape buildings be cause the latter can not fulfill the requirements of Route 1.

The purpose of the second-phase design is to protect the buildings with minor damage but no collapse nor harm of human lives by the severe earthquakes which may occur less than one time in the life time of the buildings. The second phase design, basically several checking for some structural demands, and the specifications prescribed by the Ministry of Construction as shown in [B], [C] and [D] of Fig.4. What structural fabrication are made in the first-phase design, they are demanded for checking in the second-phase design.

Check for Story Deformation Angle ([B] of Fig.4) : The story drift at every floor level $\delta_i$ under the action of lateral seismic shear force $Q_i$ prescribed in Eq.(1) are calculated by the elastic analysis. Then the story deformation angle $R_i$ is to be checked by the following expression.

$$R_i = \delta_i \;/\; h_i \;\leq 1/200\; rad \qquad (11)$$

where, $h_i$ : height of $i$-th story. The value of $R_i$ can be released up to 1/120 *rad* in the case the non-structural members shall have no severe damage at the released story deformation angle. The story deformation angle calculated under the action of seismic shear force prescribed by Eq.(1), *i.e.* for the first-phase design. Under the action of severe earthquake prescribed in the second-phase design, the story deformation angle shall be much larger than that prescribed by Eq.(11).

Check for Rig.dity Factor ([C] of Fig.4) : In the design of a building, uniform rigidity in the vertical direction should be maintained if possible, or should be designed very carefully when that can not be maintained under some special circumstances. Because of the nonuniformity in the vertical direction, the deformation may concentrate in the weak-story as shown in Fig.8. In the event of an earthquake, the collapse of the buildings due to the lack of uniformity in the vertical direction, or in other words, due to the concentration of the dissipation of energy in the weak-story, had been observed very often. To prevent this type of collapse, check for rigidity factor $R_{si}$ is necessary, and which is to be done by the following expressions.

$$R_{si} = r_{si} \;/\; r_s \;\geq 0.6 \qquad (12)$$

$$r_{si} = 1 \;/\; R_i \qquad (13)$$

$$r_s = \sum_{i=1}^{n} r_{si} \;/\; n \qquad (14)$$

If one or more stories do not satisfy this requirement, the building must be checked for the horizontal load carrying capacity, *i.e.* to go back to follow the Route 2 of Fig.4.

Check for Eccentricity Factor ([C] of Fig.4) : As of the rigidity in the vertical direction of a building, the regularity in the planning of the building should be maintained. A building with irregular plan is subjected to much greater vulnerability of earthquake than a building with regular plan. The eccentricity factor should be checked for a building to avoid poor performance in the event of a major earthquake. As shown in Fig.9, $(g_x, g_y)$ is the center of gravity of the total mass above the story being considered. The center of gavity can be obtained from the following equations.

$$g_x = \Sigma(N\,x) \;/\; W \qquad (15a)$$

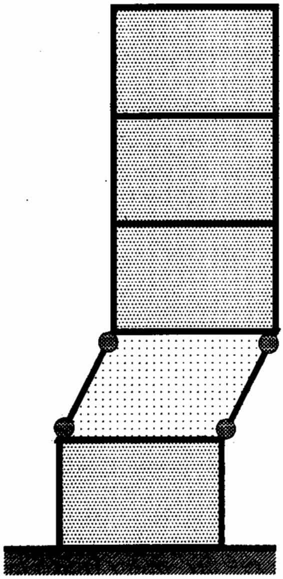


Fig 8. Concentration of Energy Dissipation in Weak-Story

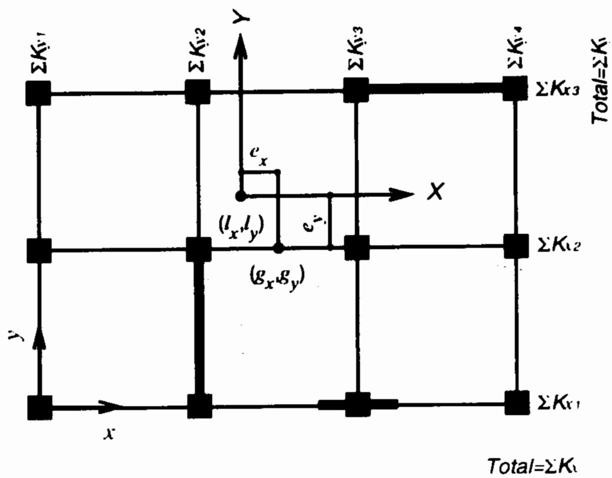



Fig 9. Building with Eccentricity

$$g_y = \Sigma(N\,y)\ /\ W \qquad (15b)$$

where, $N$ is the axial force in column, shear wall, and $W = \Sigma N$ in the story being considered. The center of rigidity i.e. the center of rotation ($l_x$, $l_y$) under the action of torsional moment can be obtained from the following equations.

$$l_x = \Sigma\,(K_y\,x)\ /\ \Sigma K_y \qquad (16a)$$

$$l_y = \Sigma\,(K_x\,y)\ /\ \Sigma K_x \qquad (16b)$$

where, $K_x$ and $K_y$ are the transitional stiffness in $x$ and $y$ axes. The eccentric distances in the axes of $x$ and $y$ are $e_x$ and $e_y$, as shown in the figure and can be obtained from the following equations.

$$e_x = |\ l_x - g_x\ | \qquad (17a)$$
$$e_y = |\ l_y - g_y\ | \qquad (17b)$$

The eccentricity factors $R_{ex}$ and $R_{ey}$ are to be checked by the following expressions.

$$R_{ex} = e_y\ /\ r_{ex}\ \leq 0.15 \qquad (18a)$$

$$R_{ey} = e_x\ /\ r_{ey}\ \leq 0.15 \qquad (18b)$$

where, $r_{ex}$ and $r_{ey}$ are the elastic radii defined by the following equations.

$$r_{ex} = (K_R\ /\ \Sigma K_x)^{1/2} \qquad (19a)$$
$$r_{ey} = (K_R\ /\ \Sigma K_y)^{1/2} \qquad (19b)$$

where, $K_R$ is the rotational stiffness, defined by the following equation.

$$K_r = I_x + I_y = \Sigma(K_x\,Y^2) + \Sigma\,(K_y\,X^2) \qquad (20)$$

where, $I_x$ and $I_y$ are the components of rotational stiffness in the axes of $x$ and $y$. The $X$ and $Y$ are defined by the Fig.9.

If one or more stories do not satisfy the requirement of Eq.(18), the building must be checked for the horizontal load carrying capacity, i.e. to go back to follow the Route 2 of Fig.4.

Check for Specifications ([C] of Fig.4) : The minimum requirements specified by the Ministry of Construction must be checked in addition to the checks for rigidity and eccentricity factors.

(1) RC or SRC buildings : In the case of RC or SRC buildings, one of the three conditions prescribed as follows must be satisfied. But this requirement can be bypassed if the shear walls, columns, and beams possess sufficient seismic strength and ductility, which are confirmed by experimental study.

(a) The following empirical equation must be satisfied for every story.

$$\Sigma 250 A_w + \Sigma\,70\,A_c \geq 0.75\,Z\,W\,A_i \qquad \textit{for } R \quad (21a)$$
$$\Sigma 250 A_w + \Sigma 100\,A_c \geq 0.75\,Z\,W\,A_i \qquad \textit{for } S \quad (21b)$$

(b) Or, the following empirical equations must be satisfied for every story.

$$\Sigma 180A_w + \Sigma\, 180A_c \geq Z\,W\,A_i \qquad \textit{for RC} \qquad (22a)$$
$$\Sigma 200A_w + \Sigma\, 200A_c \geq Z\,W\,A_i \qquad \textit{for SRC} \qquad (22b)$$

The empirical Eqs.(21),(22) are converted from *kgf* to *N* by approximating 1 *kgf* = 10 *N*.

(c) Or, to ensure the energy dissipation capacity of the frame, all columns and beams must be designed so that premature shear failure is prevented.

(2) Steel buildings : Each story which has braces to carry horizontal forces shall meet the condition that the force in those members due to design seismic force must be increased by a multiplication factor $A$ according to the following expressions.

$$A = 1 + 0.7\,b \qquad \textit{for}\ b \leq 5/7 \qquad (23a)$$

$$A = 1.5 \qquad \textit{for}\ b > 5/7 \qquad (23b)$$

where, $\beta$ is the ratio of horizontal force carried by the braces to the total story shear of the story being considered.

Check for Horizontal Load Carrying Capacity ([D] of Fig.4) : The ultimate lateral shear strength of each story shall not be less than the lateral shear $Q_{un}$ determined in accordance with the following equation.

$$Q_{un} = D_s\, F_{es}\, Q_{ud} \qquad (24)$$

where, $D_s$ : structural characteristics factor (Table 2); $Q_{ud}$ : seismic shear in a story for severe earthquake (calculated by Eq.(1),(2) taking $C_o$ not less than 1.0); $F_{es}$ : the shape factor which shall be the product of $F_s$ and $F_e$ as given below.

$$F_{es} = F_e\, F_s \qquad (25)$$

where $F_e$ : basic shape factor determined as a function of the eccentricity factor $R_e$ as of Eq.(19).

$$F_e = 1.0 \qquad \textit{for}\ R_e \leq 0.15$$

$$F_e = 1.0 + 0.5/0.15(R_e - 0.15) \qquad \textit{for}\ 0.15 < R_e < 0.3 \qquad (26)$$

$$F_e = 1.5 \qquad \textit{for}\ R_e \geq 0.3$$

and $F_s$ : basic shape factor determined as a function of the rigidity factor $R_s$ as of Eq.(12).

$$F_s = 1.0 \qquad \textit{for}\ R_s \geq 0.6$$

$$F_s = 1.0 + 0.5/0.3(0.6 - R_s) \qquad \textit{for}\ 0.3 < R_s < 0.6 \qquad (27)$$

$$F_s = 1.5 \qquad \textit{for}\ R_s \leq 0.3$$

**Table 2 Values of Structural Characteristics Factor $D_S$**

| Structure | Steel Structures | | | Reinforced Concrete Structures | | |
|---|---|---|---|---|---|---|
| Type / Characteristics | $\beta \leq 0.3^{*1}$ | $0.3 < \beta \leq 0.7^{*2}$ $0.3 < \leq 0.5^{*3}$ | $\beta > 0.7^{*2}$ $\beta > 0.5^{*3}$ | $\beta_u \leq 0.3$ | $0.3 < \beta_u \leq 0.7$ | $\beta_u > 0.7$ |
| Most Ductile | 0.25 | 0.30 | 0.35 | 0.30 (0.25) | 0.35 (0.30) | 0.40 (0.35) |
| Very Ductile | 0.30 | 0.35 | 0.40 | 0.35 (0.30) | 0.40 (0.35) | 0.45 (0.40) |
| Ductile | 0.35 | 0.40 | 0.45 | 0.40 (0.35) | 0.45 (0.40) | 0.50 (0.45) |
| Others | 0.40 | 0.45 | 0.50 | 0.45 (0.40) | 0.50 (0.45) | 0.55 (0.50) |

Note: Figures in paranthesis are for steel reinforced concrete structures

$\beta$ : ratio of horizontal force carried by the braces to the total story shear of the story being considered

$\beta_u$ : ratio of horizontal force carried by shear walls to total story shear of the story being considered

*1 for $\lambda e \leq 500/\sqrt{F}$ *2 for $500/\sqrt{F} < \lambda e \leq 900/\sqrt{F}$ or $\lambda e$ $2000/\sqrt{F}$

*3 for $900/\sqrt{F} <$ le $< 2000/\sqrt{F}$ (the limiting values of le are converted from tonf/cm$^2$ by approximating 1 tonf/cm$_2$ = 100 MPa)

where l2 : effective slenderness ratio of bracing, F : yield strength (MPa)

**An Especial Concept on Reinforced Concrete Buildings ($h \leq 20m$)**

Reinforced concrete buildings whose height is not more than 20$m$, are common in Japan for apartment houses usually constructed by using plenty of RC walls. These buildings need not be subjected to the second-phase design for earthquakes. The exemption of the second-phase design for these buildings was examined from a technical point of view by Shiga, with respect to damage observed in the 1978 Miyagiken Oki Earthquake (Umemura 1979).

Figure 10 shows wall area index in $cm^2/m^2$ in the horizontal axis and average shear stress in $N/cm^2$ in the vertical axis. The plotting of the buildings with severe damage are shown by cross marks and those with slight or no damage are by small circles. The buildings which are outside the shaded rectangle area bounded by $A_w/\Sigma A_f$=30$cm^2/m^2$ and $W/(A_c+A_w)$=120$N/cm^2$, suffered slight or no damage, while those which

are inside the rectangle suffered severe damage or collapsed. Therefore, this rectangle area may be regarded as "dangerous area".
With a seismic hazard zoning coefficient $Z$=1.0, lateral shear distribution factor $A_i$=1.0 (for first story), and the average weight of a building may approximately assume to be 10,000 $N/m^2$, *i.e.* $W$=10,000$\Sigma A_f$ ($N$), then the Eq.(10a) becomes

$$\Sigma 250A_w + \Sigma 70A_c = 10{,}000 \, \Sigma A_f \, (N) \qquad (30)$$

This curve is introduced in the Fig.10, which revealed that the buildings in the area lower-right of the curve are roughly in the safe area, although they were subjected to the earthquake with maximum recorded acceleration from 250 to 300 $cm/sec^2$ (*gal*). This clearly indicates that these type of buildings do not require the second-phase design.

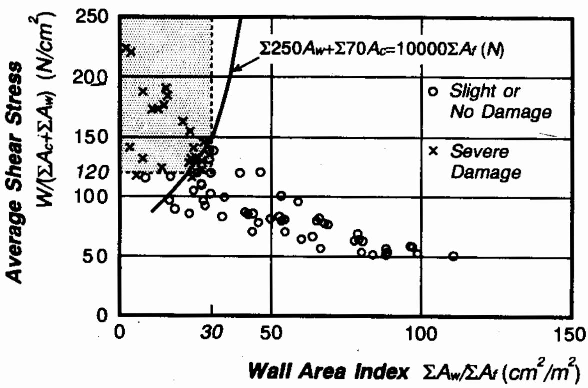



Fig 10. Wall Area Index-Average Shear Stress

**Design of Highrise Buildings ([E] of Fig.4)**

As shown in Fig.4, the current building standard law in Japan provides the design procedure of the buildings up to 60$m$ in height. Whenever a building exceed that limit, then its structural design is subjected to special approval from the Ministry of Construction. The approval depends on the recommendation of the Structural Review Committee for Highrise Buildings of the Building Center of Japan. In practice, a highrise building is designed by a group of structural engineers who have their vast technical knowledge and experience. There is a set of earthquake resistance design criteria shown in Table 3. These criteria seems to be on the traditional basis, but in practice the buildings are designed by taking greater serviceability and safety provisions depending on the condition of the site of construction.

Design Mechanism : Weak beam - strong column mechanism is usually assumed in the earthquake resistance design, *i.e.* hinges are permitted to form (a) at the end of beams, (b) at the end of exterior column subject to tensile force, and (c) at the top of the uppermost stories. This mechanism is assumed in order to dissipate the hysteretic energy uniformly throughout the structure, and the total deformation at the top of the building would be distributed over the total height.

Design for Level 1 Earthquake Motions : The serviceability corresponds to the Level 1 earthquake motions. The Level 1 earthquake motion is the largest earthquake motion which would occur once during the lifetime of a building. A building must satisfy a set of criteria for serviceability for Level 1 earthquake motions, that is the structure must be serviceable immediately after the earthquake. The criteria are (a) story deformation angle must be less than 1/200 *rad*, (b) no structural member should develop yielding, and (c) no non-structural elements should be damaged.

The seismic design loads are determined by taking reference of the provisions of Building Standard Law, and modifying by a preliminary earthquake response analysis, according to the requirement and judgment of the designers. Therefore, it is a structural analysis for design loads (permanent and temporary load) for proportioning the members. Plane frame analysis for regular and space frame analysis for irregular buildings are carried out. The purpose of the design is to protect the formation of yield hinging assumed in the mechanism under the Level 1 earthquake load.

Design for Level 2 Earthquake Motions : The safety corresponds to the Level 2 earthquake motion. The Level 2 earthquake motion is the largest earthquake motion which would occur in a possible maximum time at a construction site. A building must satisfy a set of criteria for safety for Level 2 earthquake motions. The criteria are (a) story deformation angle must be less than 1/100 *rad*, (b) yielding is permitted but with full resistance, at some designated locations, and (c) brittle failure should not take place in any member.

The assumed mechanism whether can be formed under the action of Level 2 earthquake is ensured in this design. And also the ultimate load carrying capacity is evaluated, which is similar as of [D] of Fig.4. The ultimate load carrying capacity may be evaluated by limit analysis. But nonlinear frame analysis is also adopted which can give the ultimate load carrying capacity and load-displacement relation.

Earthquake Response Analysis : The serviceability and safety of the building is checked by earthquake response analysis of the designed building. A simplified analytical model "lumped mass shear model" is exclusively used by the designers in the time history earthquake response analysis for both Level 1 and Level 2 earthquake motions. But the nonlinear dynamic response of three dimensional frame analysis can give more accurate prediction of response behavior and the response characteristics of all elements can be verified by this analysis. The input earthquake ground motions, which are prescribed by the Building Center of Japan are as follows (Building Center of Japan 1986).

| | | |
|---|---|---|
| (1) Standard Ground Motions: | | |
| El Centro | 1940 NS | (341.70 *gal*) |
| Taft | 1952 EW | (175.95 *gal*) |
| (2) Long Period Component Ground Motions: | | |
| Hachinohe | 1968 NS | (225.00 *gal*) |
| | EW | (182.90 *gal*) |

(3) Regional Ground Motions:

| | | |
|---|---|---|
| Tokyo-101 | 1956 NS | ( 74.00 *gal*) |
| Osaka-205 | 1962 EW | ( 25.00 *gal*) |
| Sendai THO 30-1FL | 1978 EW | (202.57 *gal*) |

The input earthquake ground motions are normalized by the velocities recommended at Level 1 and Level 2 earthquake motions (Table 3) and the stable velocity of the Velocity Spectrum obtained by the analysis.

**Table 3 Earthquake Resistance Design Criteria for Highrise Buildings**

| Earthquake Motions | Level 1 | Level 2 |
|---|---|---|
| Maximum Ground Velocity | 25 cm/sec | 50 cm/sec |
| Stroy/Memeber Ductility Factor | < 1.0 | < 2.0 |
| Story Deformation Angle | < 1/200 rad | < 1/100 rad |

P - Delta Effect : The *P - Delta* effect is important in a highrise building because the axial force in the lower story columns is significant. If the response story deformation angle exceeds 1/80 *rad*, or if the fundamental natural period of a structure is longer than 4.0 *sec*, the *P - Delta* effect should be included in the analysis (Otani, Teshigawara, Murakami and Okada 1994).

**CONCLUSIONS**

Learning lessons from major earthquakes in this century, Japan could propose a rational earthquake design method, known as two-phase design method to resist two level of earthquake excitation (moderate and major). Basically, the first-phase design based on working stress design, is to withstand the buildings against moderate earthquakes, and the second-phase design is to check for safety of the buildings against major earthquakes by checking ultimate strength and other properties of the buildings. But this design method is limited to the buildings, which does not exceed 60*m* in height.

Buildings exceeding 60*m* in height regarded as highrise buildings, which are designed for two level of earthquake excitation based on earthquake response analysis. The serviceability and safety of the buildings are checked by the analysis while the structural design is carried out by experienced engineers taking reference from a set of standard earthquake resistance design criteria. The structural design of these buildings must be revised by Structural Review Committee of Building Center of Japan before getting approval for constructions.

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## NOTATIONS

$A$ = multiplication factor
$A_c$ = area of columns
$A_f$ = floor area
$A_i$ = shear distribution factor
$A_w$ = area of shear walls
$C_i$ = seismic shear coefficient of $i$-th story
$C_o$ = standard shear coefficient
$D_s$ = structural characteristics factor
$e_x, e_y$ = eccentric distances in $x$ and $y$ axes
$F$ = yield strength
$F_e$ = basic shape factor function of eccentricity factor $R_e$
$F_{es}$ = shape factor product of $F_e$ and $F_s$
$F_s$ = basic shape factor function of rigidity factor $R_s$
$g_x, g_y$ = coordinates for center of gravity
$H$ = depth of basement from ground level
$h$ = height of building

$h_i$ = height of $i$-th story
$I_x, I_y$ = components of rotational stiffness in $x$ and $y$ axes
$K_R$ = rotational stiffness
$K_x, K_y$ = transitional stiffness in $x$ and $y$ axes
$k$ = seismic design coefficient of basement
$k_a$ = seismic design coefficient of appendage
$l_x, l_y$ = coordinates for center of rotation
$N$ = axial force in column and shear wall
$n$ = number of stories
$Q_i$ = seismic shear of $i$-th story above ground level
$Q_B$ = seismic shear in basement
$Q_p$ = portion of the seismic story shear force in adjacent upper story
$Q_{ud}$ = seismic shear in a story for severe earthquake
$Q_{un}$ = lateral shear
$q$ = seismic shear of appendage
$R_e$ = eccentricity factor
$R_{ex}, R_{ey}$ = eccentricity factors in $x$ and $y$ axes
$R_i$ = story deformation angle
$R_s$ = rigidity factor
$R_{si}$ = rigidity factor of $i$-th floor level
$R_t$ = vibration characteristics factor
$r_{ex}, r_{ey}$ = elastic radii in $x$ and $y$ axes
$r_s$ = average value of $r_{si}$
$r_{si}$ = reciprocal of story deformation angle $R_i$
$T$ = fundamental natural period of structure
$T_c$ = critical period of subsoil
$W$ = weight of the portion of building being considered
$W_B$ = weight of basement due to dead and live loads
$W_i$ = weight of building above $i$-th story
$w$ = weight of appendage
$X, Y$ = distances measured from center of rotation in $x$ and $y$ axes
$Z$ = seismic hazard zoning coefficient
$\alpha$ = ratio of height of stories to total height $h$
$\alpha_i$ = ratio of weight of building above $i$-th story to total weight
$\beta$ = ratio of horizontal force carried by braces to total story shear
$\beta u$ = ratio of horizontal force carried by shear walls to total story shear
$\delta_i$ = story drift at $i$-th floor level
$\lambda e$ = effective slenderness ratio