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RECENT DEVELOPMENTS IN SEISMIC DESIGN CRITERIA IN JAPAN

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ABSTRACT

Current seismic design criteria in the Building Standard Law of Japan are briefly introduced (a) for the allowable stress design procedure and (b) for the examination of ultimate story shear resisting capacity. The design earthquake forces are specified in terms of story shear rather than floor horizontal forces as a function of fundamental period of a structure and the dominant period of a construction site with a base shear coefficient of 0.20 in a short-period range of structures for the allowable stress design, and with that of 1.0 for the examination of story shear resisting capacity. Required story shear capacity may be reduced by considering the deformation capability of hinging members, and increased by considering the irregularity of structural configuration. The Architectural Institute of Japan proposed a set of design guidelines for reinforced concrete buildings on the basis of the capacity design concept, and also a set of design guidelines for steel structures based on the limit state design procedure. A research project is under way to develop a new performance-based design procedure to replace the Building Standard Law.

KEYWORDS

Earthquake resistant building design criteria, Performance-based design, Prescriptive requirements, Building Standard Law of Japan, Capacity design, Limit states design, AIJ design guidelines

INTRODUCTION

Separate design regulations have been prepared separately for civil engineering structures and building structures in Japan. The following standards and specifications have been prepared for civil engineering constructions by corresponding organizations in charge (IAEE, 1992); *i.e.*, (1) Earthquake Resistant Construction Methods of Water Supply Facilities (Japan Waterworks Association), (2) Design Manual of Port and Harbor Structures (Japan Port and Harbor Association), (3) Highway Bridge Design Specifications (Japan

Road Association), (4) Standard Design for Steel Highway Bridges (Japan Road Association), (5) Design Manual of Substructures of Highway Bridges (Japan Road Association), (6) Design Standards of Structures (Japan Railways), (7) Design Standards of Dams (Japan National Committee on Large Dams), (8) Technical Recommendations for Aseismic Design of Nuclear Power Plants (Japan Electrical Society), (9) Specifications for Earthquake Resistant Design of Sub-merged Tunnels (Japan Society of Civil Engineers), and (10) Standard Design Specifications for Concrete Structures (Japan Society of Civil Engineers).

The Building Standard Law of Japan was proclaimed in May 1950 to safeguard the life, health and property of people by providing minimum standards concerning the site, structure, equipment and use of all buildings built in the country. The methods of construction and structural requirements (loads and resistance) are specified in the Building Standard Law Enforcement Order, which has been revised from time to time to meet the technical development. However, the assumptions and methods of structural calculation are not included in the Law Enforcement Order because such are believed to be an established procedure in engineering that should not be controlled by the government. The Architectural Institute of Japan (AIJ) provides engineering procedures through various standards for structural calculation and design guidelines, which are normally deemed as technical references and technical recommendations by the academia.

BUILDING STANDARD LAW REQUIREMENTS

The Building Standard Law Enforcement Order was revised in July 1980 to the present form, and was enforced from June 1981. The revision was based on the recommendation of the Integrated Technical Development Project, entitled "Development of New Earthquake Resistant Design (1972-1977)." A significant revision was made on the structural design requirements for earthquake resistant buildings: *e.g.*,

(1) Design and construction of a building was made possible up to 60 m in height; the design and construction of buildings taller than 60 m must be specially approved by the Minister of Construction,

(2) Design earthquake forces were specified (a) in terms of story shear rather than of floor horizontal forces, (b) as a function of fundamental period of the structure and the dominant period of site, (c) at two levels (allowable stress design and examination of story shear resisting capacity), and (d) also for the underground structures,

(3) Additional requirements were introduced in structural calculation; *e.g.*, (a) story drift limitation under elastic design earthquake forces, (b) the examination of story shear resisting capacity at the formation of a collapse mechanism, (c) reduction in the required story shear capacity by deformation capability of hinging members, and (d) increase in the required story shear capacity in a story with low story stiffness or high mass-stiffness eccentricity, and

(4) Alternative simple procedures were introduced for the examination of story shear resisting capacity.

The structure must be designed using the allowable stress procedure and then the ultimate story shear resisting capacity of the structure as designed must be examined at the formation of a collapse mechanism.

Allowable Stress Design

The seismic story shear coefficient C_i for the allowable stress design procedure is calculated by the following expression:

$$C_i = Z\, R_t\, A_i\, C_o \tag{1}$$

where, Z: seismic zone factor (= 0.7 to 1.0), R_t: vibration characteristic factor (design earthquake spectral shape function), A_i: factor representing vertical distribution of the seismic story shear coefficient, C_o: base shear coefficient (= 0.2). The vibration characteristic factor R_t is defined as a function of natural period T of the structure and the estimated dominant period T_c of the subsoil (0.4 sec for stiff sand or gravel soil, 0.6 sec for other soil, and 0.8 sec for alluvium mainly consisting of organic or other soft soil) as follows:

$$\begin{aligned} R_t &= 1.0 && \mathit{for} \quad T < T_c \\ R_t &= 1.0 - 0.2\{\frac{T}{T_c} - 1\}^2 && \mathit{for} \quad T_c \leq T < 2\,T_c \\ R_t &= 1.6\,\frac{T_c}{T} && \mathit{for} \quad 2\,T_c \leq T \end{aligned} \tag{2}$$

The natural period of the building may be calculated by

$$T = (0.02 + 0.01\alpha)\,H \tag{3}$$

in which H: total height of the structure in m, and α: ratio of stories by steel and timber construction. The coefficient A_i is given by the following expression:

$$A_i = 1 + (\frac{1}{\sqrt{\alpha_i}} - \alpha_i)\,\frac{2\,T}{1 + 3\,T} \tag{4}$$

where $\alpha_i = \sum_{j=i}^{n} W_j \,/\, \sum_{j=1}^{n} W_j$, and $\sum_{j=i}^{n} W_j$: total of dead and live loads above story i. The seismic coefficient k of underground part of a building is given by the following expression;

$$k \geq 0.1\,(1 - \frac{D}{40})\,Z \tag{5}$$

where D: depth in meters below the ground level, but regarded as 20 in excess of 20 m.

The inter-story drift under the elastic design earthquake forces must be not more than 1/200 of the inter-story height. The stress in any structural member caused by the combination of the gravity loads and design earthquake forces must not exceed the allowable stress of materials; the allowable stresses are normally full yield stress for steel and two-third compressive strength for concrete. These requirements are believed to satisfy the serviceability requirements under a medium intensity ground motion.

Story Shear Resisting Capacity

Each story of a building must retain a story shear resisting capacity greater than the required story shear capacity Q_{un}, in which an elastic story shear coefficient C_i in Eq. (6) is modified in Eq. (7) considering the ductility and irregularity of the story.

$$C_i = Z\, R_t\, A_i\, C_o \tag{6}$$

$$Q_{un} = D_s\, F_{es}\, C_i \sum_{j=i}^{n} W_j \tag{7}$$

where, Z, R_t, A_i are the same as in Eq. (1). C_o: base shear coefficient for the examination of story shear resisting capacity (=1.0), D_s: structural characteristic factor, F_{es}: structural configuration factor, $\sum_{j=i}^{n} W_j$: total dead and live loads above story i.

Structural characteristic factor D_s is specified for each story and separately for timber construction, steel construction and reinforced concrete construction on the basis of expected deformation capacity of those members which develop yielding or failure at the formation of a collapse mechanism. An example is shown for a reinforced concrete building in Table 1. The deformation capacity of a reinforced concrete column, for example, is estimated by (a) clear height to width ratio, (b) tensile reinforcement ratio, and (c) failure mode, axial stress and shear stress levels relative to concrete strength developed in the column at the formation of a collapse mechanism.

Table 1: Structural Characteristic Factor D_s for Reinforced Concrete Buildings

	Ratio of Story Shear Resisted by Walls in Structure		
Performance of Structure	Less than 30 %	30 - 70 %	More than 70 %
Excellent Ductility	0.30	0.35	0.40
Good Ductility	0.35	0.40	0.45
Reasonable Ductility	0.40	0.45	0.50
Others	0.45	0.50	0.55

Structural configuration factor F_{es} is calculated as the product of factors F_s and F_e representing the irregularity of stiffness distribution in height and eccentricity in plan, respectively. The regularity in stiffness distribution along the structural height is judged by the value of rigidity ratio R_{si} at story i, defined by the following expression;

$$R_{si} = \frac{r_{si}}{\bar{r}_s} \tag{8}$$

in which, r_{si}: reciprocal of story drift angle at story i, $\bar{r}_s$: average value of r_s's at all stories. Factor F_s representing stiffness distribution in height is $F_s = 1.0$ for $R_{si} \geq 0.6$, $F_s = 1.5$ for $R_{si} \leq 0.30$, and interpolated in a range of $0.3 < R_{si} < 0.6$. Eccentricity ratio R_{ei} of story i is defined as a ratio of eccentricity e_i between the center of total mass above the story and the center of rotation under the action of torsional moment to the elastic radius r_{ei} of gyration of the stiffness (square root of the ratio of sum of squares of torsional resistance to the sum of the square of the lateral resistance) of story i.

$$R_{ei} = \frac{e_i}{r_{ei}} \tag{9}$$

Mass center is defined for the column axial loads developed by the gravity (sustained) load above the story. Lateral stiffness of vertical member is estimated as a ratio of the shear of the vertical member divided by the story drift of the member. Factor F_e representing the eccentricity is $F_e = 1.0$ for $R_{ei} \leq 0.15$, $F_e = 1.5$ for $R_{ei} \geq 0.30$, and interpolated in a range of $0.15 < R_{ei} < 0.30$.

The story shear resistance of a story is calculated as a story shear at the formation of a collapse mechanism under the lateral force distribution similar to the elastic earthquake forces given by Eq. (1). The ultimate flexural resistance and shear resistance of each member are calculated using the material strength as the specified compressive strength for concrete, and 1.1 times the specified yield strength for reinforcing bars and steel. The material strength of shear reinforcement must be the specified yield strength of the shear reinforcement, but not more than 3,000 kgf/cm^2. The story shear resistance must be larger than that given by Eq. (7).

Simple Examination of Story Shear Resisting Capacity

Those reinforced concrete buildings (a) not more than 20 m in height, and (b) satisfying the following dimensions of columns and walls are not required to examine the story shear resisting capacity because the structure is judged to possess a sufficient lateral load resistance;

$$\sum 25\, A_w + \sum 7\, A_c \geq Z \sum W_i\, A_i \tag{10}$$

in which A$_w$: horizontal area of structural walls in the direction of earthquake force (cm^2), A_c: horizontal area of columns in the direction of earthquake force (cm^2), Z: seismic zone factor, $\sum W_i$: sum of dead and live load above story i (kgf), A_i: factor representing vertical distribution of the seismic story shear coefficient. Values 25 and 7 represent the approximate shear strength per unit horizontal area of walls and columns.

Those reinforced concrete buildings of (a) total height $H \leq 31\, m$, (b) story drift angle $r_s \leq 1/200\, rad$ under elastic design earthquake forces, (c) rigidity ratio $R_{si} \geq 0.6$, and (d) eccentricity ratio $R_{ei} \leq 0.15$, are judged to be regular in configuration and may satisfy any of the following three conditions:

(a) $\sum 25\, A_w + \sum 7\, A_c \geq 0.75\, Z \sum W_i\ A_i$ (11)

(b) $\sum 18\, A_w + \sum 18\, A_c \geq Z \sum W_i\ A_i$ (12)

(c) Girders and columns do not fail in shear against shear calculated by assuming yielding at the member ends.

PROPOSALS BY ARCHITECTURAL INSTITUTE OF JAPAN

The Architectural Institute of Japan (AIJ) has published various design guidelines and standards for structural calculation for building structures since the first publication of "Standard for Structural Calculation of Reinforced Concrete Structures" in 1933. The concept of the ultimate story shear resisting capacity in the Building Standard Law Enforcement Order was further extended for reinforced concrete structures in "Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept (AIJ RC Design Guidelines; AIJ, 1991)," in which the concept of the capacity design was introduced. Limit states design procedure was proposed for steel structure (AIJ, 1990).

The application of the AIJ RC Design Guidelines is limited to a structure of regular configuration and overall height up to 45 m because some of design coefficients were developed for limited cases. The basic concept is to allow the formation of plastic hinges only at specified regions where a large ductility can be easily obtained such as beam ends. The required resistance at probable locations of plastic hinge formation is determined to limit the story drift under imaginary design earthquake motions to an acceptable range (a story drift less than 1/100 of the story height); the plastic deformation capability is examined at the plastic hinge locations corresponding to twice the limiting story drift. The regions not permitted to form plastic hinges must be provided with sufficient resistance for flexural yielding and shear failure, taking into consideration (a) scatter of material properties from the design specified values, (b) contribution of higher modes of vibration, (c) reliability of calculations of member strengths, (d) concurrence of bi-directional horizontal earthquake motions, and (e) uncertainties involved in selecting the characteristics of design earthquake motions.

TOWARD PERFORMANCE-BASED DESIGN SYSTEM

Ministry of Construction, Japanese Government, partially responding to the Gaiatsu (foreign pressure) to open the Japanese construction market to foreign participation, initiated an Integrated Technical Development Project, entitled "Development of New Structural Design System for Buildings (April 1995-March 1998)." The project was aimed to review the problem of present Building Standard Law System and to develop a new and integrated system for structural design of buildings. The idea of General Agreement on Tariffs and Trade (GATT) may be realized by adopting performance-based specifications for a set of loading conditions instead of prescriptive design requirements different from a country to another. Performance criteria for a building and loading conditions may be different from a country to another, but the method of structural calculation can be common in engineering community of all countries.

All buildings in Japan must, in principle, satisfy the technical requirements of the Building Standard Law. The methods of construction and structural calculation are specified in the Building Standard Law Enforcement Order (Cabinet Order). Minister of Construction issues technical notifications to supplement the Building Standard Law Enforcement Order and Department of Building Guidance, Bureau of Housing, Ministry of Construction, issues circular notices to clarify the technical requirements under the Building Standard Law system. Furthermore, a local public entity may prescribe, by ordinances, additional restrictions necessary for safety, fire prevention or sanitation concerning the site, construction or building equipment of buildings. Therefore, it is extremely difficult for a structural engineer to keep track of the on-going requirements for a structural design.

The conformance of all the requirements must be confirmed by building officials when the design documents are submitted to a local administrative office. A structural engineer or a building official is absorbed in satisfying or checking the requirements literally without having time to examine the technical reasons behind. A building owner and structural engineers, in most cases, are not aware of possible performance and consequence of the building under various loading conditions. Such a situation should be corrected.

Furthermore, the Building Standard Law system may not be suitable for the application and development of specialized high technology in construction because the Cabinet Order cannot specify individual requirements for the rapidly progressing technology. Prescriptive standards need to be constantly reviewed and revised with the progress in technology. Prescriptive requirements are easy to follow in the structural design, but it is difficult to evaluate the degree of achievement of target performance criteria by the prescriptive requirements unless their rational reasons are clearly described. The prescriptive design requirements will be maintained for routine design works, which do not demand higher technology.

The project should identify the desired structural performance of a building, and develop an integrated system of structural design which can meet the progress in technology, the freedom in structural design and a variety of performance specifications for a building.

The following scenario is considered for a structural design; *i.e.*, a structural designer, after consultation with the building owner, outlines a set of target structural performance criteria of a building for various loading situations, takes the actions of structural design to achieve the criteria in the building, and finally confirms the structural performance under specified loading conditions. For this, close communication and understanding between the owner and the structural engineer is essential to establish a set of target performance criteria for a particular use, nature and requirement of the building. Possible performance criteria must be carefully studied for a variety of buildings and made available to the building owner. A set of structural design criteria should be clearly established for a desired performance of the building. Various design procedures must be developed to achieve a set of structural design criteria; a structural engineer may select a procedure most suitable for the design situation. Structural engineers with higher technical background may possibly be required to carry out a performance-based structural design.

Before a set of performance criteria are discussed, the loading conditions (dead loads, live loads, snow loads, wind forces, earthquake forces, soil pressure, vibrations, impact and explosion forces and others) should be clearly defined for a particular situation. The loading amplitude and occurrence varies with space (live loads) and time (live loads, wind forces, earthquake forces), involving large uncertainties. Reliability design technique may be applied for the definition of loading.

Performance of a building may not be specified from the structural point of view alone; *e.g.*, cost, construction difficulty and period, use, serviceability (amenity, vibration, deformation, acceptable damage), safety, reliability, durability, maintenance of function during an event, repair period and cost after a damaging event. The owner of a building may choose a set of performance criteria; on the other hand the society must maintain the minimum standard for safety. The procedure to define a set of performance criteria as well as the structural design method to achieve the performance criteria may be different for the material of construction.

Reliability of construction should be improved with the refinement of structural design. The responsibility against an event must be strictly defined and identified in a contract for the architect, the structural engineer, the mechanical engineer and the construction contractor working on a project. Higher responsibility must be assigned to the structural engineer. Japanese society, as a member of Asian communities, is not trained nor prepared for this strict system and a significant social agreement and changes must be accomplished before a new performance-based design system is introduced in the society.

CONCLUDING REMARKS

Current seismic design criteria in the Building Standard Law of Japan are briefly introduced (a) for the allowable stress design procedure and (b) for the examination of ultimate story shear resisting capacity. The Architectural Institute of Japan proposed a set of design guidelines for reinforced concrete buildings on the basis of the capacity design concept, and also a set of design guidelines for steel structures based on the limit state design procedure. A research project is under way to develop a new performance-based design procedure to replace the Building Standard Law.

REFERENCES

Architectural Institute of Japan (1991), Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept (in Japanese), 337 pp., and also AIJ Structural Design Guidelines for Reinforced Concrete Buildings (1994) (in English), 207 pp.

Architectural Institute of Japan (1990), Standard for Limit State Design of Steel Structures (Draft) (in Japanese), 266 pp.

International Association for Earthquake Engineering (1992), Earthquake Resistant Regulations, A World List - 1992, pp. 23-3 - 23-90.