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TARGET SEISMIC PERFORMANCE LEVELS IN STRUCTURAL DESIGN FOR BUILDINGS

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SUMMARY

Primary objectives of the design of building structures are to 1) protect human life, 2) conserve properties and 3) maintain functions. We call the performances to achieve these design objectives as 1)safety, 2)reparability, and 3)serviceability, respectively. The performances and levels appropriate for a building structure are determined not only in terms of structural technologies but by the demands of its owners, users, and society. To examine the issues related to the target performance levels in structural design, the Target Level Subcommittee was organized in the 3-year Japanese Comprehensive Research and Development Project on "Development of a New Engineering Framework for Building Structures" which was launched in fiscal 1995. This paper describes a framework for determining levels, which is a summary of the fundamental ideas concerning target levels, and various factors that may be used for deciding levels and those used in actual evaluations.

INTRODUCTION

Building structures must have various kinds of performances, such as safety and serviceability. The performances and levels appropriate for a building structure are determined not only in terms of structural technologies but by the demands of its owners, users, and society. The conventional building design system has had no definite method nor idea for establishing target performances or levels. Although the owners and users should correctly understand target performances and target levels, it has been difficult since technical knowledge is needed to understand structural performances. Therefore, design engineers are requested to explain the target structural performances, target levels, and the significance in society using plain words that are easy for the owners and users to understand. The Target Level Subcommittee (chairperson: Prof. Yoshitsugu Aoki of Tokyo Institute of Technology) was organized in the 3-year Japanese Comprehensive Research and Development Project on "Development of a New Engineering Framework for Building Structures" which was launched in fiscal 1995. The subcommittee surveyed the ideas for determining performances and levels and conducted various related studies. The subcommittee formed a framework for determining levels, which is a summary of the fundamental ideas concerning target levels, and investigated various factors that may be used for deciding levels and those used in actual evaluations.

BASIC FRAMEWORK FOR ESTABLISHING TARGET LEVELS

This section describes briefly the framework for establishing target levels.

Building Structural Design:

Building structural design is an act of free decision-making concerning building structures, and is a principal part of building designing, in which the owner of a building and the design engineer create a new building space

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based on their values, standards, and abilities. Since it is a free act, the owner and the design engineer bear the responsibility.

Duties of the Engineer to the Owners in Structural Design:

It is universally accepted that the decisions made by the owner concerning various factors determining the performances of a building are respected. It is the duty of the corresponding design engineer to respect the decisions of the owner, cover for the lack of information and technical knowledge, and help the owner make rational decisions.

Roles of a Building Structure and Two Kinds of Demands:

A building structure must provide a space in which people feels safe and comfortable. Creation of such a space is the purpose of designing the building structure. Therefore, a building structure must possess certain degrees of performance to 1) protect human life, 2) conserve properties, 3) maintain functions, and other roles that the building is expected to play. In building structure designing, the performances should be understood in terms of 1) private demand, and 2) social demands.

Basic Framework for Deciding Target Structural Performance Levels:

Even when structural performances are understood in terms of engineering values, their target levels should be decided based on personal and social requests. the levels that should be determined based on the personal requests of the owner are those concerning 1) human safety, 2) protection of property, including the reparability of damages, and 3) functions that the building is expected to possess daily and after being damaged by a certain cause. Those that should be considered based on social requests are 1) safety of the users, visitors, and people passing near the building, and 2) the possibility of social loss in terms of damage expansion when the building is damaged.

Evaluation Indexes for Determining Target Structural Performance Levels:

There are various factors to consider for deciding target levels, which may be classified into two groups: those that cannot be restored once they are lost, such as human life and cultural assets (irreparable damage) and those that can be restored under present technical and social systems by repairing, re-constructing, or purchasing although it involves monetary loss (reparable damage). Factors of the latter group are comparable with each other in terms of a single evaluation index, money. On the other hand, the former cannot be evaluated in terms of money. Therefore, two or more evaluation indexes should be used in determining target structural performance levels.

Rule for Using Two or More Evaluation Indexes:

All target levels determined with two or more evaluation indexes must obey the following rule. A target level may be used only when there is no technical alternative that is better in one or more evaluation indexes than the decided target level and is the same in all other indexes.

Probabilistic Understanding of Phenomena:

All load and resistance phenomena are inherently random in nature, therefore they must be understood and quantified in probabilistic terms. The target levels of structural performance should be established based on accepted methods of structural reliability analysis.

Factors in Determining Structural Performance Levels:

Factors that should be considered in determining structural performance levels are 1) the performances of the building structures that have been built based on experience, 2) risks on factors other than structures, and 3) total cost throughout the period that the building is used.

The following sections described the detail of examination on each factors in determining structural performance levels.

SEISMIC PERFORMANCE LEVEL OF EXISTING BUILDINGS

Basic Concept

The current building code in Japan provides design and analysis procedures to achieve the primary design objectives such as the life safety under large earthquakes. Since the code has been accepted in the society by revising its contents reflecting the building damage by past earthquakes, it is quite reasonable to determine the target performance level of buildings in a new design procedure by referring to the performance level of existing buildings which were designed in accordance with the current code. However, the current code describe the design requirement in prescriptive way, and it doesn't describe the target performance levels explicitly. To quantify the performance level of existing buildings, the levels of design earthquake and the performance levels of model buildings are examined in terms of the return period and the reliability index,β, respectively.

Return Period of Design Earthquakes

In the current building code, two different base shear coefficients are adopted for seismic design; one is the base shear coefficient, C_0=0.2, for the design of serviceability limit state, and the other is the base shear coefficient, C_0=1.0, for the design of ultimate limit state. The seismicity of different location is considered by the seismic zone factor, Z. Figure 1 shows the maximum acceleration levels of earthquake ground motions at eight different cities in Japan. Thick lines indicate the acceleration levels of current building code obtained assuming the acceleration of 400 gal (cm/sec2) for the earthquake corresponding to the design base shear coefficient, C_0=1.0. Thin lines indicate the acceleration levels corresponding to the specific return periods obtained from the statistical data in the AIJ guideline [Architectural Institute of Japan, 1993]. Considering the large uncertainty in earthquake loads, it is reasonable to define the level of design earthquake using the return period. From the comparison in Figure 1, the current design earthquakes for the serviceability limit design (C_0=0.2) and the ultimate limit design (C_0=1.0) roughly correspond to the earthquakes with 30 year and 500 year return periods, respectively.

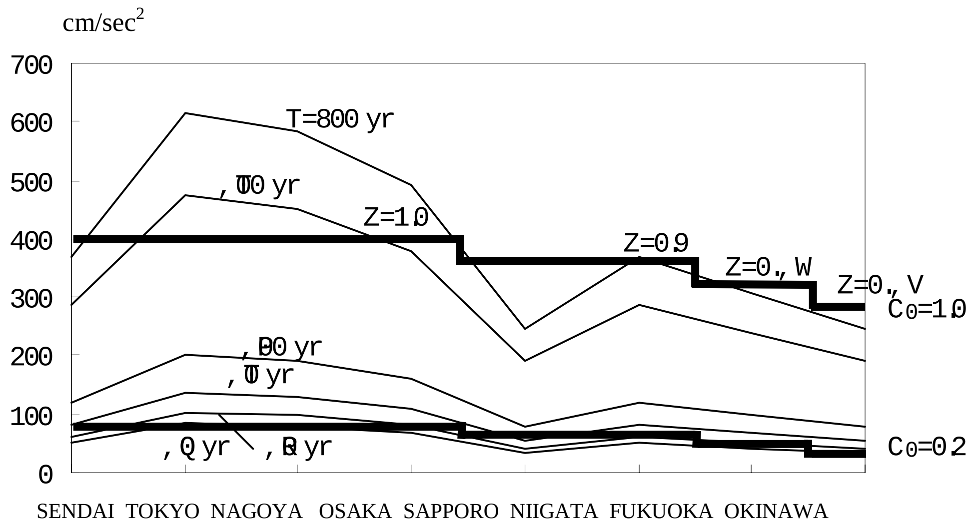
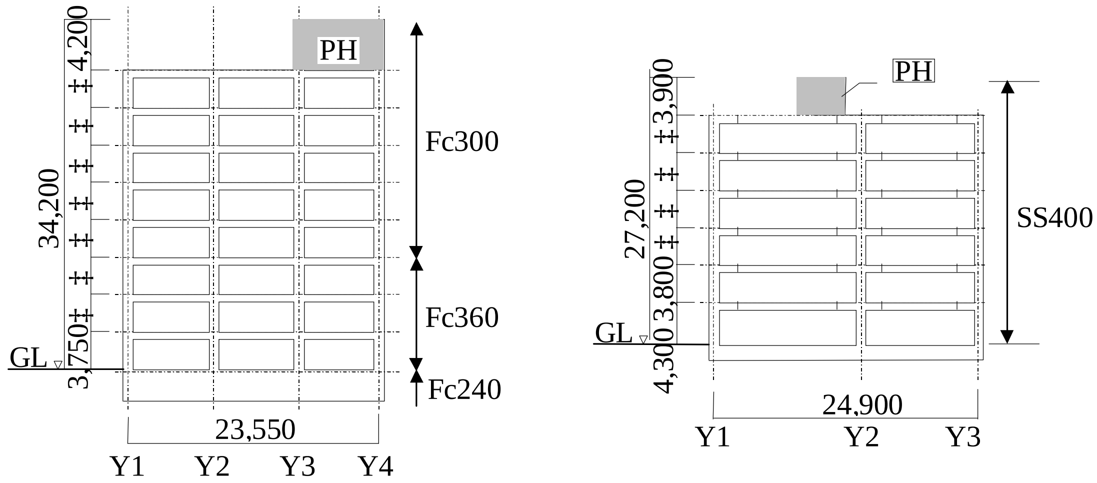


Figure 1 Maximum earthquake ground acceleration and its return period at eight cities in Japan

Seismic Reliability Levels of Existing Buildings

Seismic reliability levels of the buildings designed according to the current design code in Japan are evaluated in terms of the safety indices, β, and are compared between different construction sites; Tokyo and Osaka, as well as between the different building systems; a reinforced concrete building and a steel building. The elevation views of the buildings are shown in Figure 2. Input earthquake ground motions are modeled as nonlinear stochastic processes with certain power spectrum and deterministic envelope functions. The detail procedures to evaluate the reliability index, β, are described in the reference [Saito, Kanda and Kani, 1998]. Figure 3 shows the relation between the reliability index, β, and the maximum story drift ratio for the reinforced concrete building and the steel building. From this results, the performance items and related reliability indices are summarized in Table 1.



(a) (b)

Figure 2 Building models: (a) reinforced concrete building; (b) steel building (unit: mm)

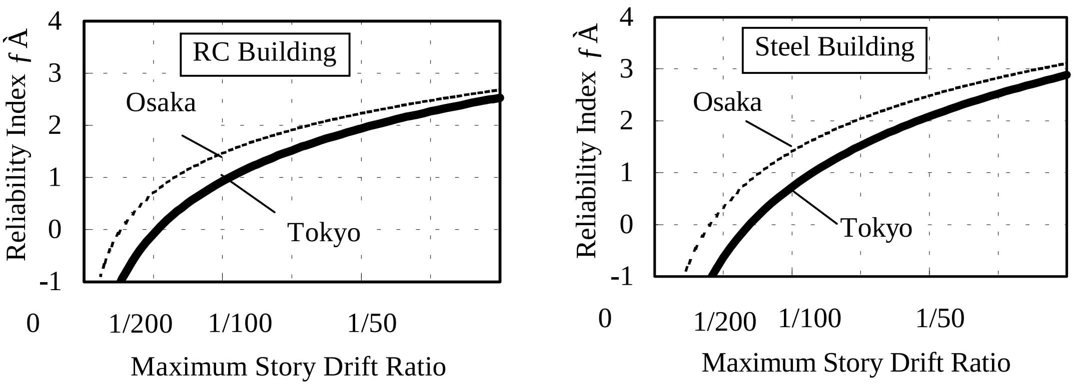


Figure 3 Seismic reliability index β for 50 years

Table 1 Example of reliability index β for building performance

Performance of building	Deformation criteria story drift ratio)	Reliability Index β (in 50 years)
Concrete crack	1/200	β = 0
Damage on secondary elements	1/100	β = 1.0
Failure of structural elements	1/50	β = 2.0
Collapse of building	1/30	β = 3.0

The conclusions drawn from the results are follows:

1) Even the design seismic zone factors are the same for both sites, the reliability index,β, of Tokyo site is generally smaller than that of Osaka site.

2) At the serviceability limit state of 1/200 maximum story drift ratio, the reliability index,β, of the steel building is found to be smaller than that of the reinforced concrete building. The result is possibly caused by the difference of elastic stiffness of the buildings.

3) At the ultimate limit state of 1/50 maximum story drift ratio, the reliability index, β, is almost the same for both type of buildings to be around 2.0.

ACCEPTABLE RISK LEVEL

Basic Concept

The targets and safety levels that a building structure should possess must be decided not only in terms of technology and economics but also with quantitative analyses of danger to human life. It is especially important to understand how the society views the safety of existing buildings. The safety performance level demanded of a building should be investigated by classifying various death risks that exist in our living environments into background risk groups. This “background risk” provides basic information to consider a social standard of the risk criteria. Figure 3 shows the statistical data of annual risks in Japan [Building Research Institute, 1998]. It is apparent that the annual risk by natural disaster is quite small comparing other risks. However, the frequency of event is not only a measure to judge its acceptability. The impact of the event to the society should be also discussed.

Risks and Expression Methods

There are many fundamental ways of expressing risks. Therefore, risk management, which involves methods for using the results of risk assessment, should be determined. Activities that may cause death should be investigated in terms of “possibility of conducting the activity” and “risk of death by the activity” separately, which need different countermeasures in terms of risk management. For example, “to limit the activity” and “to eliminate danger from the activity” are both ways of reducing the risk but are completely different measures.

Comparison of Risks and Issues Concerning Risk Regulation

The study on risks in various activities revealed the following points:

1) A difference in degree of damage causes a different degree of risk recognition even for the same act or activity.
2) A difference in activity type (active or passive, personal or social, etc.) strongly affects risk recognition.
3) The characteristics of the persons endangered (age, sex, physical conditions, economic power, etc.) affect risk recognition.

Such a study should be conducted not only by listing risks and effects but also by using the most appropriate risk and by carefully investigating the endangered groups in society and the form and degree of danger. The risk to a building structure does not seriously affect the risk to the whole of society. However, it should be noted that the safety of a building structure or the danger of earthquake damage is not a risk accompanying a voluntary act but is a risk that is unavoidable

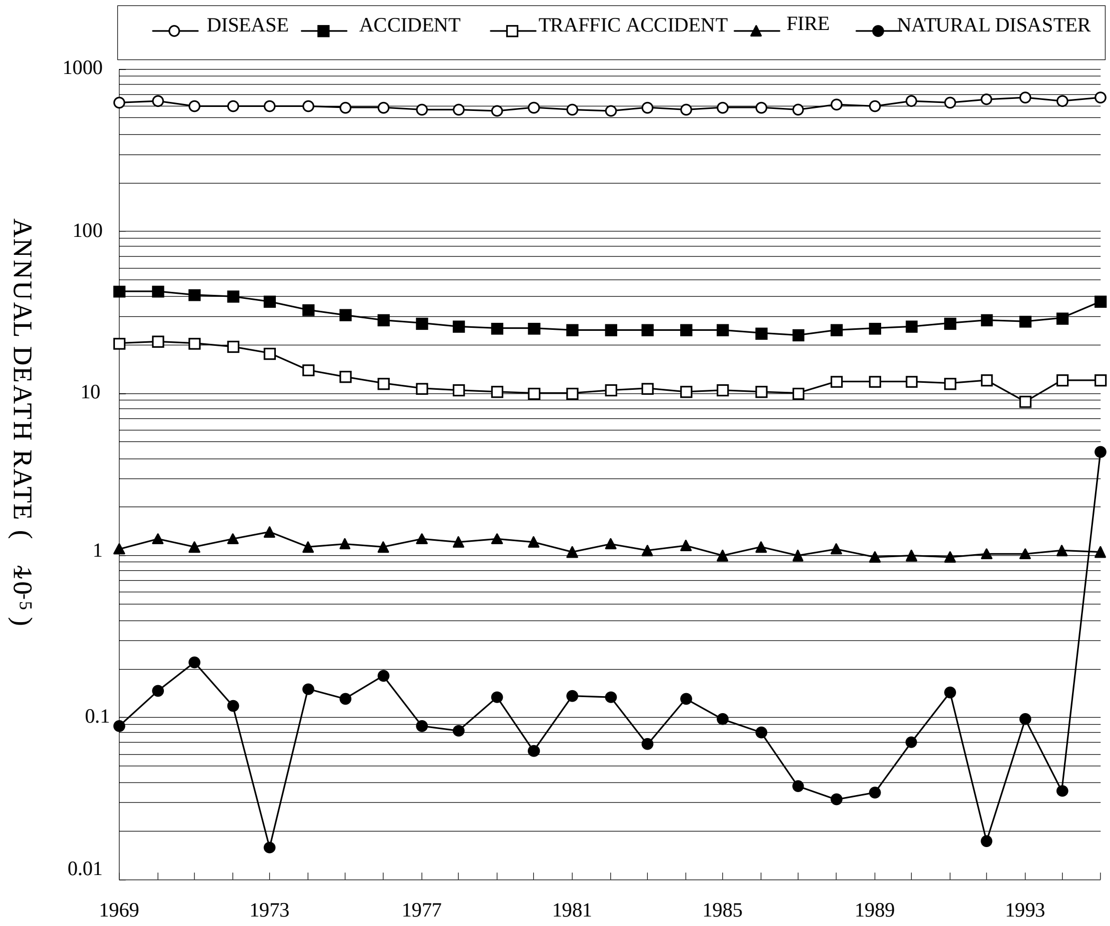


Figure 4 Annual risks in Japan (1969-1995)

MINIMUM COST LEVEL

Basic Concept

Target performance levels may be decided in terms of economics when the building is confirmed to have the required safety level concerning human life. Performance levels that require the minimum cost during the entire period that the building is used may be selected as the target levels. This concept is called the principle of minimum total cost. To consider irreparable damages, such as loss of human life, various evaluation indexes besides total cost and money must be investigated for deciding target levels.

Concept of Total Cost

In the principle of minimum total cost, total cost is the sum of the initial construction cost, the cost for maintaining the building throughout the period, and the expected value of loss caused by disasters, minus the benefit obtained during the period. Except considering the cost of maintenance and the benefit, the total cost is simply modeled by the following equation:

$$C_T = C_I (d) + C_F (d) P_F (d) \qquad (1)$$

where, C_T is a total cost, C_I is an initial construction cost, C_F is a damage cost, and P_F is a probability of the occurrence of such damage. In principle, these costs may be expressed as functions of performance levels, d. There are various measures for expressing performance levels, such as safety probability against destruction, strength of the building structure, and design external forces. The formulas for expressing the initial building cost as functions of performance levels should be determined by investigating structure designs in the past. Damage probability must be studied based on the strength of the building structure and the probabilistic and statistical characteristics of loads in order to calculate the expected loss values. The loss by a damage should include the damage to the structure, the damage to objects within the building, the damage caused by loss of functions (including loss of profit otherwise obtained), and the damage to society. As schematically shown in Figure 5, the optimum performance level is obtained as the level which minimizes the total cost.

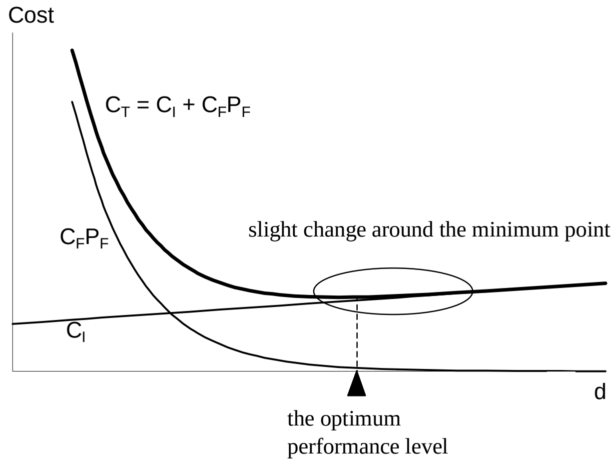


Figure 5 Principle of minimum total cost

Characteristics of Performance Levels that Minimize Total Cost

Simulation analyses [Building Research Institute, 1998] revealed that performance levels that require the minimum expected total cost values had the following characteristics:

1) In terms of the minimum-total-cost principle, the optimum levels of those buildings for which damage may seriously affect the functions and social roles should be higher than those of ordinary buildings, suggesting that the purpose, functions, and effects of building damage to the surroundings should be carefully investigated for determining performance levels.
2) Near the optimum level at which the total cost is minimum, the total-cost function shows a gentle curve, and a slight fluctuation in level does not greatly change the expected total cost value. Since the levels of most existing buildings are within this gentle range, a slight improvement of safety will not significantly raise the cost.
3) To popularize the principle of minimum total cost, models and methods that make it easy for design engineers to analyze damage and the resultant costs should be developed.

CONCLUTIONS

In the subject of determining target performance level of building structures, the following facts may be pointed out from the study in this report:

Evaluation of the Safety Levels

General people understand the need for legal regulations to prevent damage spreading to other people, but do not fully recognize that the law prescribes minimum levels and allows certain degrees of damage to buildings during large earthquakes. Since the present legal regulations are based on specifications, the safety levels they prescribe are not clear and may be affected by load environments and structural types. Therefore, in the first step of target level determination, the safety levels prescribed by the law should be objectively and quantitatively stated to help design engineers and the owners of buildings understand the levels. The safety levels of buildings designed to meet the conventional laws may be evaluated by using the structural performance evaluation method that uses reliability indices, which was developed in this study. A study on background risks showed that the risks on existing building structures do not increase the risks to the whole of society.

Determination of Levels Adequate for the Building Usage

Even in the conventional design system, it has been possible to flexibly determine design targets if they satisfied the legal regulations. However, many structures were designed based on the minimum standards and just aimed to satisfy the laws and regulations. The concept of a coefficient of building usage or importance coefficient does not exist in the conventional system. Only a few owners, regional administrative bodies, and governmental facilities have established target levels higher than the minimum standards by incorporating the importance coefficient against an earthquake to increase earthquake resistance or by establishing a deformation limit. The study showed that citizens want, and it is economically , to use target levels higher than ordinary levels for buildings that may be seriously damaged or may affect other buildings or persons during a disaster. A study on background risks showed that the risks are high for people who may be easily affected by damage, such as handicapped persons, and should be carefully investigated.

Ranking Performance Levels

One way of determining target levels is to select performance levels from performance ranks of serviceability, reparability, and safety, all of which satisfy the levels prescribed by the law. Technologies and systems should be developed for improving structural designs of levels just satisfying the minimum requirement into those of higher performance levels to meet the purposes and importance of the building, to protect urban and social functions, and to meet the needs of the owners. Performance levels should be ranked in terms of economic rationality and protection of human safety. The principle of minimum total cost may be used for making economic decisions. It is also necessary to help general consumers correctly understand the differences in performance levels.

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