New Framework for Performance Based Design of Building Structures
-Design Flow and Social System-

by

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ABSTRUCT

This paper introduces the outline of the new structural engineering framework and social system for the performance-based design of building structures proposed under the 3-year Comprehensive Research and Development Project on "Development of a New Engineering Framework for Building Structures" was launched in fiscal 1995. In the project, the clarification of target performance, the evaluation of performance and the indication of performance, are emphasized as the main three elements of this framework. The implementation of the proposed framework is also expected to promote engineering innovation, the progress in building engineering, and globalization.
Key Words :Performance-based Design,
Performance Evaluation,
Target Performance Level,
Social System

1. INTRODUCTION

The present structural design framework prescribes the design load and external force, as well as the allowable stress and deformation, but does not specify the performance requirements explicitly. Only detailed calculation methods are specified without clear indication of target performance and building performances (Figure 1).

As a result of that, the present framework cannot explain explicitly the real building performance and is becoming increasingly inappropriate for new technologies and performance indication. Then it has been needed to establish a new "performance-based structural design framework". This framework would also encourage the communication between consumers and engineers in order to make a consensus on building structural performance, and the application of new materials and new technologies, by its rational performance requirements and its flexibility in evaluation of performance.

To establish such a performance-based framework, a 3-year Comprehensive Research and Development project on "Development of a New Engineering Framework for Building Structures (referred to below as Comprehensive R&D Project)" was launched in fiscal 1995. The concept of the performance-based structural design has been discussed in the technical coordinating committee of the project (Chairman: Prof. Dr. Tsuneo OKADA). Three sub-committees are organized under the technical coordinating committee.

This paper introduces the outline of the concept and the framework of Performance Based Design (P.B.D.) with the structural performance evaluation system discussed in the "Performance Evaluation" sub-committee (Chairman: Prof. Dr. Hiroshi AKIYAMA), the target performance of buildings structures and their levels from various point of view in "Target Performance Level" sub-committee (Chairman: Prof. Dr. Yoshitsugu AOKI), and the social background and supporting systems should be to conduct P.B.D. practice

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smoothly in the market in the "Social System sub-committee (Chairman: Dr. Katsumi YANO)".

This paper introduces the outline of the performance based structural framework in a stage of research. So, this framework should be reconsidered in adopting into the regulation or code, for example Building Standard Law.

2. OBJECTIVES

The primary objective of the new framework is to create an system in which the performance of buildings is clearly indicated and "consumers" (owners and users) are well informed of how their buildings perform and how much it costs to attain the performance (design, supervision and construction costs). The new framework would also bring about other benefits, such as progress in building engineering and design techniques, greater flexibility in design, and closer international cooperation. It is important to clarify target performance and verify by the rational performance evaluation method, so that the building performance satisfies the target performance initially clarified.

Such an approach allows more flexibility in choosing design techniques and calculation methods, because it aims to understand performance requirements, and to clarify the target performance and evaluate the building performance rationally.

Next, it is important for engineers to explain the building structural performance to owners, users, and the public. In the process of decision of target performance, engineers are expected to communicate with owners, in order to understand the requirements of owners, and to make advices to them from the engineering and public point of view. Then, users and the public are able to understand the building performance.

Moreover, it is also important that the building structural performance will be one of the most important measures for consumers to define the building value. As a result of that, the concept of cost-performance is treated in structural engineering by the new framework with a performance-based approach.

3. CONCEPT OF THE NEW PERFORMANCE-BASED DESIGN FRAMEWORK

Figure 2 shows a flow of the new performance-based structural framework proposed by the Project (referred to below as the "new framework"). The new framework consists of three key procedures: "clarification of target performance", "evaluation of performance" and "indication of performance".

At the first stage of (frame-1), "Basic Structural Performances" which are primarily required for the building structures are established. Safety, Reparability and Serviceability are itemized as the Basic Structural Performance.

In the second stage, "Basic Structural Performances" which are described as the "Limit States" for each "Performance Evaluation Item" in general expression in the frame-3. The types of loads or external forces and their magnitude in the frame-2 are set along with setting of the frame-3. Performance levels of each performance evaluation item should be defined by the relationships between the magnitude of loads and external forces which affects to the structure, and the limit states that the structure should be in.

The performances evaluated in the frame-4 of each evaluation items should be indicated clearly in the frame-5.

4. CLARIFICATION OF TARGET PERFORMANCE

In principle, the target performance of a building is clarified how the building should perform according to each performance evaluation items, i.e. the state of the structural frame and each building elements under assumed loads and external forces. To do so, it is necessary to study the performance requirements for the building (items and levels of the performance required).

First of all, a building is required to have public functions. Buildings have certain meanings in the society and have to be suitable for the general public, or society. The minimum requirements of building performance are defined in the code. Building is required to have functions specific to its usage. In other words, a building should fulfill essential functions that can be understood with its context in the public.

Next, there are needs or requirements of building owners and users. Any owner or user has some ideas of the building performance they require, however vague they might be, based on the information available to them. These requirements might be classified into those required generally by owners and users and those specifics to each case.

On the other hand, the engineering performance of a building has been based on the judgements of the experts in structural engineering, based on empirical records of damages caused by loads and external forces of past earthquakes and other events. In recent years, however, explicit methods of making such expert judgement have been developed.

By using available methods, structural engineers will specify the target performance of each building that would reflect the requirements of lay "consumers".

4.1 Basic Structural Performance

Three basic structural performances, Safety, Reparability and Serviceability are itemized. Each of them corresponds to security of human lives, security of property from the viewpoint of easiness to repair, and security of serviceability, respectively. Table 1 describes the objectives and the contents to evaluate these basic structural performances.

4.2 Performance Evaluation Items and Limit States

The combination of basic structural performances and the objects to be evaluated are defined as Performance Evaluation Items. Limit state for each performance evaluation item is listed in general expression in Table 2. In the left column of Table 2, the objects to be evaluate are enumerated. These are structural frame, structural member, non-structural member, equipment/machine, fixture, furniture and soil. Structural member and non-structural member might be arrange into one term as building members.

For example, safety limit state of structural frame is defined as that the destruction directly affects human life should be avoided. And in the safety limit of the building member, it is defined that falling out or scattering of building members that directly affects human life should be avoided. Safety limit state for safety performance, reparability limit state for reparability performance, and serviceability limit state for serviceability performance are set.

4.3 Types and Magnitude of Loads and External Forces

Usual loads (such as dead or live loads, buoyancy, negative friction, soil pressure, water pressure etc.), unusual loads of snow, wind, earthquake, other forces such as temperature stress, special soil or water pressure etc. should be considered. The magnitude of loads and external forces and their combination might be set corresponding to the three basic performances level; considering social situation, and frequency of occurrence.

The idea of design earthquake load in that scheme is introduced in Appendix I.

4.4 Performance Level

Performance levels of each performance evaluation item will be indicated by the relationships between the magnitude of loads and external forces which affects to the structure, and the limit states which the structure should be in.

Performance levels themselves can be determined by designer and owner as the distance from empirical reference level such as code requirement, or a reliability method, etc.

Some issues which need to be considered in determining the performance level of buildings are discussed in Appendix II.

5. DESIGN AS A SOLUTION TO FULFILL THE TARGET PERFORMANCE

Structural design is carried out to attain the target performance. Note that a structure means the structural system as a whole here, which involves not only the structural frame but also every building element including interior and exterior members, equipment, devices, furnishings and grounds.

The structural engineers practice their philosophy in developing a structural system that realizes the target performance. For example, several solutions may be possible when trying to attain the target performance of a structural frame to resist earthquakes; the engineers can either design the structural frame to bear the seismic forces and energies on its own, or use some devices to control the responses. In either way, detailed measures are developed through studies. The new framework will thus encourage technological innovation, such as the development of new structural frames or new devices. This will eventually motivate the structural engineers to embrace technological development.

After determining the details, the structural engineers prepares drawings and specifications, on which construction works are to be based.

6. EVALUATION OF PERFORMANCE

"Evaluation of Performance" is conducted in the third stage according to the "Principle of Performance Evaluation"; the response value should not exceed the limit value to satisfy the performance level. The performance level is represented by engineering expression in this stage.

Some definite evaluation methods will be developed in accordance with this flow to realize "The Principle of Performance Evaluation."

The performance level is represented by engineering expression in this stage. "Evaluation of Performance" is conducted according to the following steps.

1) Quantitative determination of the magnitude of loads and external forces

Magnitude of loads and external forces are determined in accordance with reliable materials relating to the background and the setting method.

2) Set the type of engineering value used for the response value and limit value

Suitable types of engineering value for response value and limit value should be determined for performance evaluation. Not only force, but displacement, velocity, and acceleration, energy, etc. can be selected for evaluating the structural performance. It means that the structural performances are defined by engineering terminologies.

3) Establishment or calculation of the limit value

The limit value which satisfies the limit state should be established (calculated or judged) according to the items describing the quantitative determination method of limit states values.

4) Calculation of the response value

The response value should be calculated by the suitable analytical method.

5) Comparison of the response value with the limit value

The response value should be compared with the limit value and confirm the performance level.

Practical methods for evaluating the structural performance and designing are necessary to be developed in accordance with this "Principle of Performance Evaluation" flow. The principle of performance evaluation should promote the renewal of the conventional evaluation method, following to the development of social fulfillment and the advancement of evaluation technology. Accordingly, detailed performance evaluation or design methods established by current knowledge are only exemplified in order to renew easily or select practically.

7. INDICATION OF PERFORMANCE

The evaluated performance should be indicated for each performance evaluation items. For example, destruction of structural frame which affects human lives directly by ○○ (loads or external forces) will almost be avoided. Probability for satisfying the basic performances may also be indicated.

This ultimately serves as a bridge between the engineers and society, i.e. consumers (owners, users and the public) of buildings. Easily, indication of building performance will become one of the key roles of structural engineer. This new responsibility will eventually give a recognized social status to the profession that society can rely on. The recognized structural engineers would be those who can clearly explain to the public how the buildings' performance was achieved at reasonable cost.

By the new framework, the performance required by the public for building structures is translated into the target performance by the structural designer in the technological domain. The engineers work to achieve this target performance and then announces the actual performance to the public.

8. SOCIAL SYSTEM

In order to make buildings actually performance-based-designed and the objective of this Project fulfilled, new "Social System" has to be developed, which is composed of various supporting devices for P.B.D. practice like social codes/rules, institutions, technical tools, information systems, etc. The outline of the new Social System and its necessary elements are as follows:

(1) Process of P.B.D.

P.B.D. can be assumed to be conversion between three phases of information related to structural performance: "Design Brief, identifying clients' needs and other requirements for the project", "Design Criteria, specifying target performance for the project" and "Design Solutions, verified to comply with the Design Criteria". P.B.D. is carried out through the following process:

a) Identifying needs about expected performance through appropriate communication between the structural engineer and the client (consequently supporting the clients to develop the Design Brief)

b) Developing the Design Criteria including the structural design policy, target performance and verification methods

c) Obtaining the approval for the Design Criteria from the client

d) Developing the Design Solutions (i.e. repeating cycles of preparative design and its verification of conformity to the target performance)

e) Presenting verified performance of the Design Solutions to the client

f) Delivering Design Solutions and other necessary information (e.g. construction methods, quality control conditions, supervision methods, etc.) to the production/construction stage

(2) Need for functions of the new Social System

The following four functions are to be attained by the new Social System:

--- Functions mainly beneficial to clients ---

a) To support clients to concretize their needs based on correct understanding of structural performance

b) To ensure sufficient reliability of conversion of clients' needs into target performance

c) To ensure sufficient reliability of conversion of target performance into performance of Design Solutions

--- Function mainly beneficial to engineers ---

d) To prepare appropriate environment for those who intend to implement the P.B.D. practice

(3) Framework for the elements of the new Social System

To fulfill the four expected functions, the framework of the Social System should be as shown in Table 3. They need to be developed to cover any of the following three types of P.B.D. practice.

a) "Individualized objective-oriented type" -- To set target performance fittest for the needs and design and verify the solutions by unique, individualized manner

b) "Standardized verification method type" -- To set or choose target performance within given range or menu, design freehand and verify the solutions utilizing ready-made methods

c) "Dependent on deemed-to-satisfy solutions type" -- To set or choose target performance within given range or menu and design and verify the solutions depending on ready-made prescriptive (deemed-to-satisfy) design guide

(4) Key Elements of the new Social System

Various elements need to be developed within the above mentioned framework.

The followings are examples of key elements.

- Performance certification service
- Structural design information managing system
- Quality assurance scheme for structural design practice
- Information system on abilities and qualifications of engineers and organizations
- Data base of reference technical information
- Evaluation system for technical tools
- Standard guide of design practice and model contract documents
- Independent bodies to provide technical services for engineers
- Insurance system suitable for P.B.D. practice
- System to support engineers to acquire knowledge and ability

9. CONCLUSIONS

In this paper, The Performance-Based Design Framework was outlined. This framework would encourage the making consensus between consumers and engineers on building structural performance, and the application of new materials and new technologies, by its rational performance requirements and its flexibility in performance evaluation. The new framework explained here would result in proper recognition of high-quality technologies, and would ultimately improve the performance and quality of building structures. And the building structural performance would be one of measures for consumers to define the building value.

The following items are considered as R&D subjects and the guideline give the directions.

1) Background study to determine the magnitude of loads and external forces.

2) Determination methods for limit value which can be represent the limit state appropriately.

3) Calculating / analytical methods for response value which can be represent the response appropriately.

4) Monitoring the performance of building, especially after earthquake.

5) Indication methods of evaluated performance

6) To make sure the structural designer (including inspectors) can carry out their jobs smoothly in the new framework, it is essential to set up the suitable social system including technological tools, customs and institutional arrangements which affect the structural designer's practice.

ACKNOWLEDGMENTS

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REFERENCES

1) The Building Center of Japan, and Japan Institute of Construction Engineering: Fiscal 1995 Report of Development of a New Engineering Framework for Building Structures, March 1996.

2) Building Research Institute, Ministry of Construction, The Building Center of Japan, and Japan Institute of Construction Engineering:

Fiscal 1996 Report of Development of a New Engineering Framework for Building Structures, March 1997.

Table 1 Basic Structural Performance (required performance)

1) Safety

Purpose :

To avoid hazard which directly affects human lives inside and outside of the buildings. (Security of human lives)

Contents to evaluate the performance :

To prevent the loss of supporting capacity of structural elements and soils which supports vertical forces from the viewpoint of safety.

To prevent the falling out or scattering of building elements (structural members, nonstructural members), equipment/machines, fixtures and urniture from the viewpoint of safety.

2) Reparability

Purpose :

To maintain the function against the damage caused by the outer stimuli (actions) to the buildings. (Security of property)

Contents to evaluate performance :

To control the deterioration and/or damage degrees on structural frames, building elements. (structural members, nonstructural elements), equipment/machines, fixtures, furniture and soil from the viewpoint of easiness for repair.

3) Serviceability

Purpose :

To secure the serviceability (function and habitability) of the buildings. (Security of serviceability)

Contents to evaluate the performance :

To eliminate harmful deformation or vibration on structural frames, building elements (structural members, nonstructural members) and members, equipment/machines, fixtures, furniture and soil from the viewpoint of human sense and building function.

※ Deterioration of material properties and affected damage during the lifecycle of building should be considered as a factor in the evaluation of every basic structural performances.

Table 2 Evaluated Objects and Fundamental Performance

Perform. / Limit state / Objects	Safety (keep of Human Life)	Reparability (keep of Properties)	Serviceability (keep of Function and Habitability)
	Safety Limit	Reparability Limit	Serviceability Limit
Structural Frame	Non-destruction*1 to human life	*within* Assigned Damage	Non-Harmful*2 Def. or Vib. for normal use
Building Members (Structural/ Non-Structural Members)	Non-drop, Scatter to human life	*within* Assigned Damage	Non-Harmful*2 Def. or Vib. for normal use
Equipment/ Machines/ Fixture	Non-Overturn, Drop, Movement by deformation or vibration of structural frames or members	*within* Assigned Damage by deformation or vibration of structural frames or members	Non-Harmful*2 Def. or Vib. of structural frames or members for normal use of equipments / machines
Furniture	Non-Overturn, Drop, Movement by deformation or vibration of structural frames or members	*within* Assigned Damage by deformation or vibration of structural frames or members	Non-Harmful*2 Def. or Vib. for normal use
Soil	Non-destruction*1 (decrease of support ability or change*3 of soil)	*within* Assigned Damage (decrease of support ability or change*3 of soil)	Non-Harmful*2 Change*3 for normal use of buildings or traffic

<Supplement>

(*1) destruction: loss of supprting capacity of structure elements and soil which supports vertical forces

(*2) harmful: available without interference in the usual usage

(*3) change: landslide, movement, deformation, decrease of stiffness (ex. by liquefaction), gap, crack of soil

Table 3 Framework of the new Social System

Expected functions / Type of sub-systems	Mainly beneficial for clients			Mainly beneficial for engineers
	(a) To support clients to concretize their needs	(b) To ensure sufficient reliability of conversion of clients' needs into target performance	(c) To ensure sufficient reliability of conversion of target performance into performance of Design Solutions	(d) To prepare appropriate environment for P.B.D. practice
(I) Basic systems	I-a-1) Performance evaluation and certification system I-a-2) Environment to provide technical service to support concretization of needs	I-b-1) System to ensure reliability of conversion process	I-c-1) System to ensure reliability of design and performance verification process	I-d-1) System to define liability and responsibility of each body involved I-d-2) System to support engineers to acquire necessary knowledge/abilities I-d-3) Environment in which P.B.D. practice can be economically feasible
(II) Evaluation system of engineers/ organizations	II-a-1) Qualification/ information system of engineers' consultation abilities	II-b-1) Qualification/ information system of engineers' abilities for conversion process	II-c-1) Qualification/ information system of engineers' abilities for design and performance verification process	II-d-1) Liability insurance system taking the level of qualification of engineers into account
(III) Technical information /tools	III-a-1) General information on relation between performance and its benefit III-a-2) Information on social /community needs including minimum requirements stipulated in building regulations	III-b-1) Technical information on conversion process III-b-2) Service by independent bodies to evaluate the result of conversion, etc.	III-c-1) Technical information on design and performance verification process III-c-2) Service by independent bodies to evaluate Design Solutions, verification and technical tools, etc.	III-d-1) Technical information for acquirement of knowledge/ abilities III-d-2) Technical information, technical evaluation system of independent bodies, etc. provided by bodies who have liabilities for them

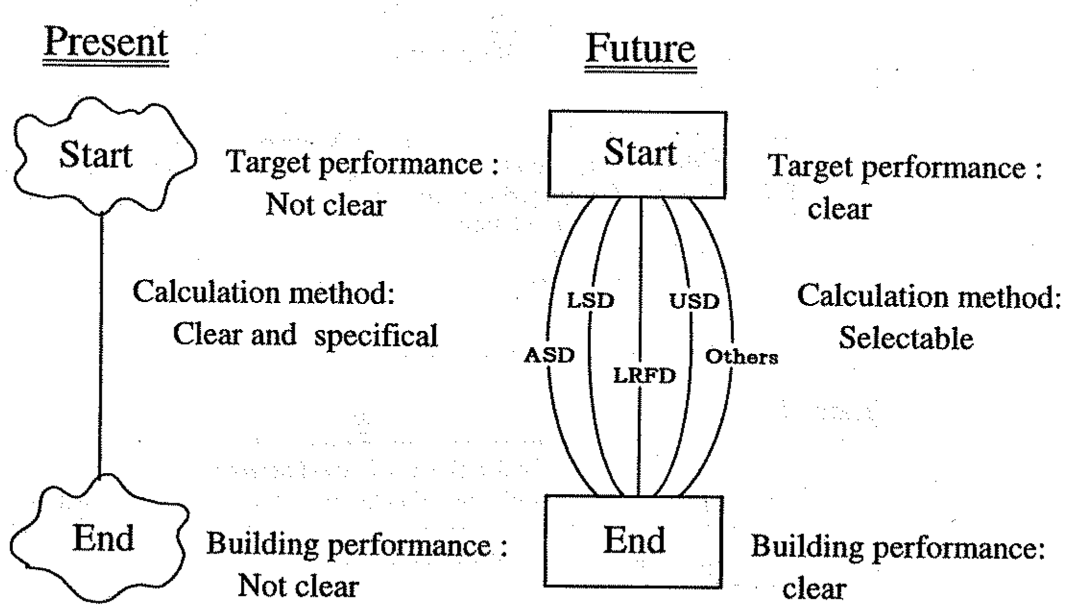

Figure 1 Present and Future Structural Framework

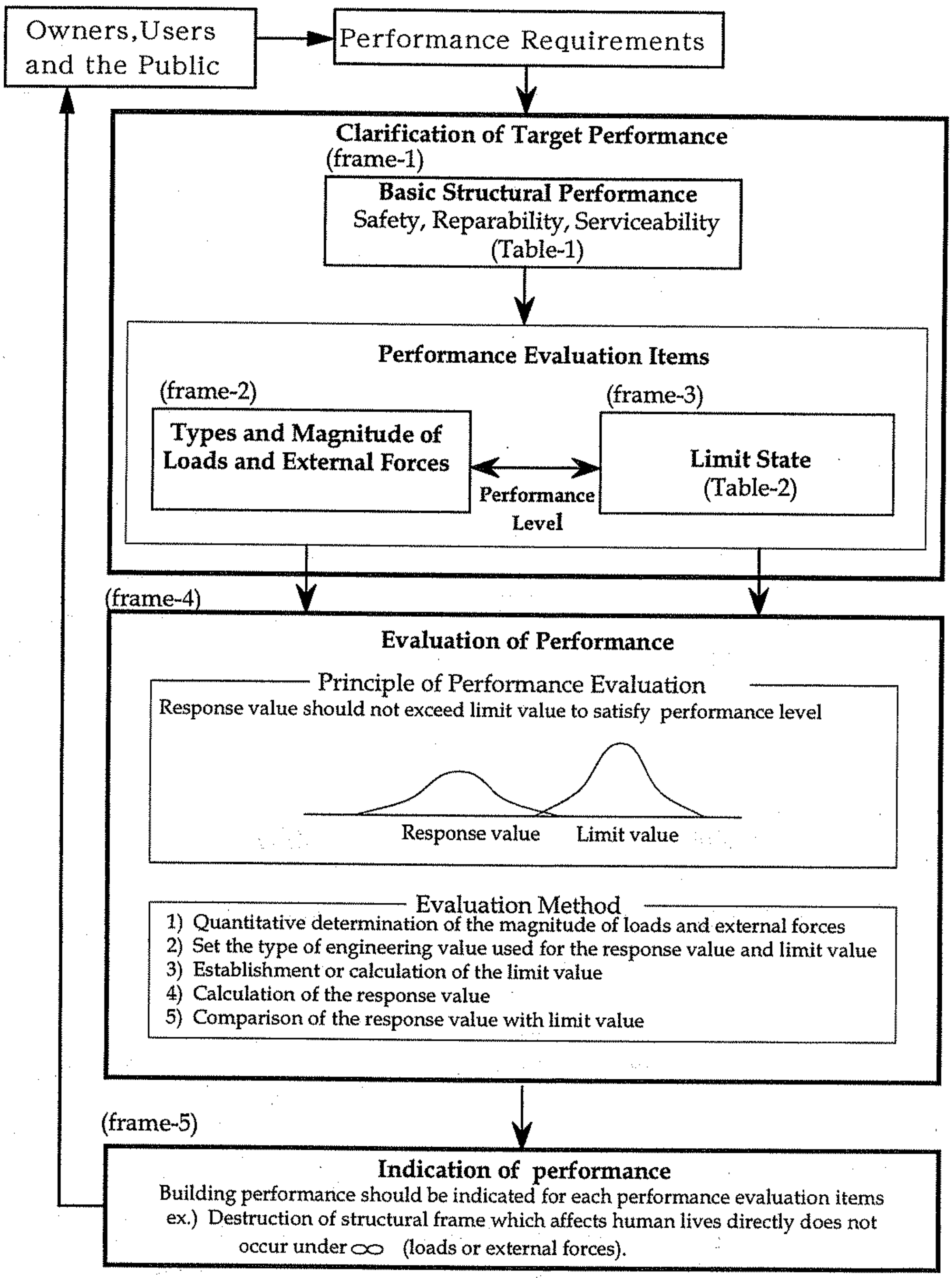

Figure 2 Evaluation system of Structural Performance

APPENDIX I. New Design Earthquake Motion

A.I.1 Design Earthquake Motion

The followings are the basic concept of our proposal for prospective design seismic force in performance-based design scheme (BRI proposal).

In our new proposal, the design earthquake load is specified with earthquake ground motion not with seismic force. The earthquake Ground Motion is basically given at the engineering bedrock which is defined as larger with more than 400 m/s in shear wave velocity.

The basic concept in evaluating the design earthquake motions is expressed in the followings.

(1) Based on the historical earthquakes, active faults, seismotectonics, earthquakes shall be selected considering the intensity indices such as peak acceleration with its occurrence rate at the construction site.

(2) A site specific earthquake ground motion or its characteristics of the selected earthquakes shall be determined.

(3) The earthquake ground motion thus determined shall be modified with the effect of dynamic soil structure interaction.

(4) The ground motion will be converted into seismic force with evaluation of response of the structure

A.I.2 Evaluation of Earthquake Load

Evaluation of Seismic Activity

The seismic activity shall be estimated using the following equation.

where, E denotes earthquake, PGA represents peak ground acceleration or its alternative intensity index, Te denotes the return period of the earthquake, and PGA(Te) is the expected value during the return period Te.

The seismic activity, source mechanism, and source locations vary with site. The types of earthquake sources to be considered in design are at least in the following three conditions.

(1) Damaging earthquake in historical data

(2) Earthquake due to active faults

(3) Earthquake for which occurrence is appropriate from seismotectonics but source locations is not identified.

(3) is assumed recognizing that (1) and (2) are not completely compiled and similar earthquake can occur in any place within a seismotectonic region.

Evaluation Earthquake Ground Motion

Earthquake ground motion or its characteristics shall be evaluated by selecting the earthquakes considered at the site and with the property of source, path and site effect

(1) Case in which source mechanism should be considered.

The hypocentral distance is comparable with or less than the fault dimension, the effect of source mechanism and rupture process to the earthquake ground motion property can not be ignored. Therefore, the estimation of design earthquake ground motion should be done using model capable of taking those effects into account. For example,

$$Aij(f)=G(f,Ej)*Pij(f)*Sj(f)$$

i=1, ..., n: n : number of earthquakes to be considered

where, Aij(f): Design earthquake ground motion characteristics at ground surface or standard position

f: frequency

G(f,Ei): Source property of i-th earthquake Ei

Pij(f): Property of propagating path from i-th source to j-th site (e.g., attenuation due to distance)

Sj(f): Soil amplification property of j-th site

In estimating the earthquake ground motion, uncertainty and variation of the data and method applied should be considered, since the source mechanism and rupture process of an earthquake cannot be predicted deterministically and the underground structure above bedrock cannot be investigated thoroughly.

(2) Case in which source mechanism need not be considered

The effect of minute variation in source mechanism on ground motion in case that the hypocentral distance is larger than the source dimension, is generally small. Therefore, the following equation can be used.

$$Aij(f)=GPij(M,D,f)*Sj(f)$$

where,

GPij(M,D,f): spectrum at bedrock

D: distance from source to site

GPij(M,D,f) can be estimated by the M-A regressive equation. The long-period property ascribed to deep underground structure above seismic bedrock shall be considered when it is appropriate to incorporate.

A.I.2.1 Estimation of Site Amplification Property

Site amplification property for i-th site Sj(f) shall be estimated with the amplification due to the surface soil above bedrock, the correction coefficient for topographical irregularity. However, earthquake response analysis is preferable for excessive irregular topography or in case soil amplification changes due to nonlinear response of soils.

$$Sj(f)=S1j(f)*S2j(f)$$

where, S1j(f): Amplification coefficient for surface soil

S2j(f): Correction coefficient for topographical irregularity

(1) Amplification coefficient for surface soil

When the surface soil is almost horizontally layered and the influence of excess pore water pressure is ignored, the amplification coefficient can be estimated with the predominant frequency of shear wave propagating vertically in the horizontally layered structure.

(2) Correction coefficient due to topographical irregularity

The correction coefficient due to topographical irregularity is use for considering the influence of irregular surface land form or non-horizontal layers. Therefore, in case that the surface soil is almost horizontally layered and then the influence can be ignored, the coefficient shall be one.

A.I.2.2 Evaluation of Dynamic Soil Structure Interaction Effect

The effect of dynamic soil structure interaction shall be considered since the soils supporting the foundation is not rigid. The inclusion of he effect in input earthquake motion means that the

$$Cijk(f)=Aij(f)*Ik(f)$$

where, Cijk(f): design earthquake ground motion at building foundation

Ik(f): Correction coefficient of the effect of dynamic soil structure interaction

However, when the excessive nonlinearity in soil and foundation is expected, a more realistic model should be used.

A.I.2.3 Evaluation of Earthquake Load

Earthquake load equivalent to effective input motion in fixed base condition or equivalent design earthquake load index can be obtained by the following formula

$$Dijkl(f)=Cijk(f)*Bl(f)$$

where, Dijkl(f): Design earthquake load index

Bl(f): Coefficient to translate to earthquake load such as story shear force coefficient considering the structural property.

However, since the design earthquake load index is an average or overall intensity index, it may not be able to grasp the destructiveness of the design motion. In such case, a specific method such as dynamic analysis procedure using earthquake motion time history shall be used.

APPENDIX II. Performance Level

There are many issues which need to be considered in determining the performance levels of buildings. Some of the these issues are listed below and discussed in the sections to follow.

(1) Performance Level of Existing Buildings
(2) Acceptable Risk Level
(3) Minimum Cost Level

(1) Performance Level of Existing Buildings

The current building code in Japan provides design and analysis procedures to achieve the primary design objectives such as the life safety under a large (severe) earthquake. Even the current code doesn't describe the level of safety explicitly, it has been accepted in the society by revising its context reflecting the building damage by past earthquakes. Therefore, 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.

The performance level should be examined under consideration of the possibility of future earthquake damage. Since there is large uncertainty in estimating future earthquake loads, the seismic safety of existing buildings should be examined in terms of probabilistic measures such as the reliability index β in a building life time.

- Model of buildings

Two typical buildings designed in accordance with the current design code are selected as the representatives of existing buildings; one is an 8-story reinforced concrete building and the other is a 6-story steel building. Construction sites are assumed to be in Tokyo and Osaka, Japan. Since the design seismic zone factor is the same for both sites (Z =1.0), the design shear forces are identical for both buildings. The uncertainties associated with structural properties are assumed to be negligible comparing the uncertainties of earthquake loads, and not considered in this study.

- Model of earthquake ground motions

Input earthquake ground motions are simulated referring to the guideline, "Recommendations for Loads on Buildings," published by the AIJ (Architectural Institute of Japan) in 1993. This study assumes that the maximum earthquake acceleration and the ground amplification factor are random variables. - Seismic reliability estimate

Sample input ground motions are generated and the nonlinear response analyses of the designed buildings are carried out. From the relation between the input scale and the maximum story drift ratio, the reliability index β is evaluated as a function of the design criterion.

Figure A.II.1 shows the relation between the maximum drift ratio Y and the safety index β for the reinforced concrete building and the steel building, respectively . As shown in the figures, the reliability index β of Tokyo site is generally smaller than those of Osaka site. The difference of the safety indices between RC building and Steel buildings in the same site is not so large.

From the calculated results, the performance of the buildings and its reliability index could be approximately summarized in Table A.II.1.

Table A.II.1
Example of Reliability Index for RC Buildings

Performance items	β *
Concrete crack	$\beta = 0$
Failure of secondary elements	$\beta = 1.0$
Failure of structural elements	$\beta = 2.0$
Collapse of building	$\beta = 3.0$

* reference period is 50 years

(2) Acceptable Risk Level

In daily life, we usually neglect the very small risk such as the risk of being hit by a comet, however, the risk of being hit by a car may not be considered negligible. If we reduce the strength of a building, the risk associated with earthquake-induced building damage may increase. So, the question is how large risk people may think acceptable, and what level of safety should be assigned to building structures.

We call the potential risk in daily life, such as the risk by disease, traffic accident, etc., as "background risk," and gathered statistical data of such risks from various sources. Obtained data are summarized into a risk database where the data of death of people are categorized by the type of causes, years, etc. The annual death ratios (=risks) in Japan by different causes are summarized in Table A.II.2.

Table A.II.2
Examples of Annual Risk in Japan

Risk items	Annual risk
Fire	10^{-5} to 10^{-6}
Earthquake	10^{-4} to 10^{-7}
Suicide	10^{-5}
Traffic accident	10^{-4}
Disease	10^{-3} to 10^{-2}

In case of earthquakes, the death ratio was evaluated by taking moving average with twenty year intervals, and it shows some fluctuation between the range of 10^{-4} and 10^{-7}. Some people reports that people will neglect the event which annual occurrence ratio is below 10^{-6}, however, when we think about the huge disaster at the Great Hanshin-Awaji earthquakes, it is clear that the frequency of event is not only a measure to judge its acceptability. The impact of the event to the society should be discussed together. Figure A.II.2 is a schematic figure showing the relation between the frequency of the risk events and their social impact, and the boundary of acceptable region may be drawn in this figure.

(3) Minimum Cost Level

Total cost of a building in its lifetime is generally modeled by the following equation:

$$C_{total} = C_{ini}(R) + C_f(R)P_f(R)$$

where, R is the design parameter of the building to represent its resistance, C_{total} is the total cost, C_{ini} is the initial cost for construction, C_f is the damage cost, and P_f is the probability of the occurrence of such damage. In this study, the damage cost C_f is assumed to consist of three different components,

$$C_f = C_{rep} + C_{los} + C_{spd}$$

where, C_{rep} is the cost for repairing the building damage, C_{los} is the cost associated with the loss of contents, and C_{spd} is the cost considering the secondary damage such as the loss of business. The initial cost, C_{ini}, is assumed to be a simple function of the parameter R, and the damage costs, C_{rep}, C_{los} and C_{spd}, are modeled as functions of the maximum story drift ratio. Figure A.II.3 shows the analytical flow to obtain the total cost by the Monte-Carlo simulations.

The optimum design parameter to minimize total cost are evaluated for various types of buildings. Table A.II.3 shows the results of for the buildings in Tokyo. In case of the private house and the office building, the minimum cost levels are found to be less than the level of current code requirement, however, in case of the school building and the hospital building, the minimum cost levels are much larger than the current design level because of the large cost of damage to their functions. These results suggest the necessity of higher performance levels of such public buildings more than the code requirement levels of general buildings.

Table A.II.3
Examples of Minimum Cost Design Levels

Building type	Minimum cost level*
Private house	92
Office	98
School	120
Hospital	200

* current design level =100

It is very sensitive issue to include the loss of human life into the calculation of damage costs. Of course, it may be possible to consider the loss of human life as the price of life insurance or cost for compensation, etc., however, it doesn't mean that the human life is equal to such costs. Therefore, we didn't include the loss of human life into the above cost calculations. Multiple design criteria including costs and human life in different axes should be discussed.

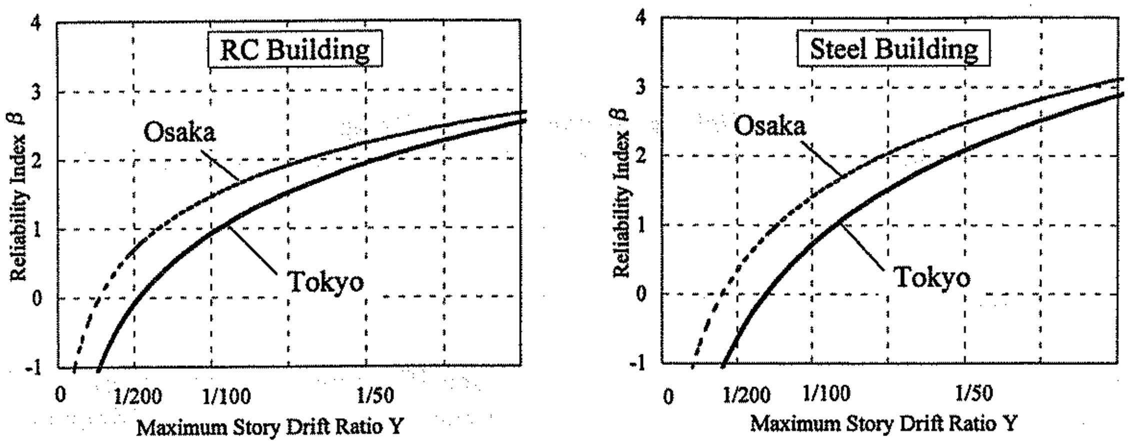

Figure A.Ⅱ.1 Relation between the maximum story drift Y and the reliability index β in 50 years

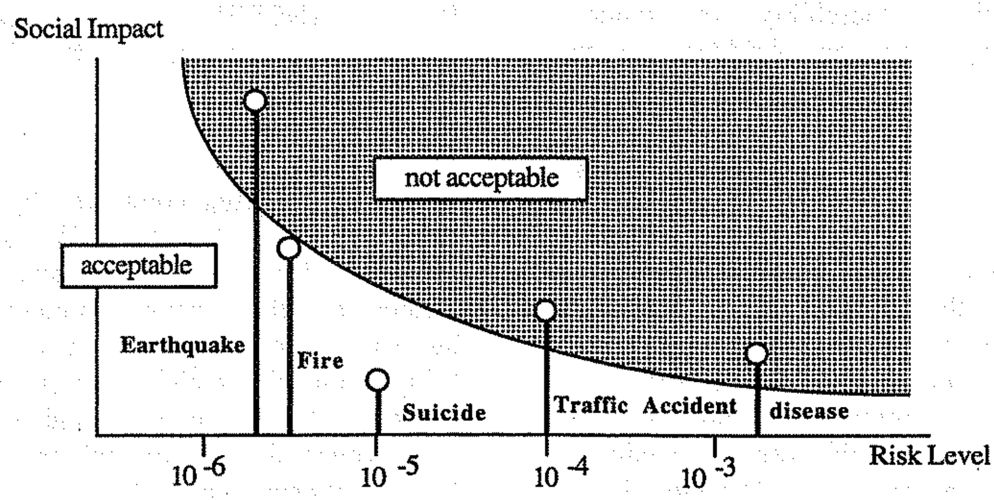

Figure A.Ⅱ.2 Concept of Acceptable Risk

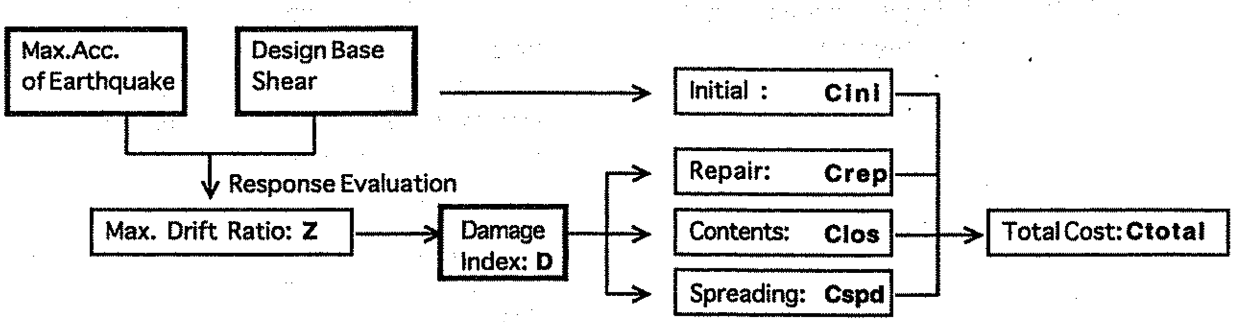

Figure A.Ⅱ.3 The Analytical Flow to Obtain the Total Cost by the Monte-Carlo Simulations