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REVIEW ARTICLE

Framework for Performance-Based Design of Building Structures

Hideo Fujitani*

Department of Architecture and Civil Engineering, Kobe University, Kobe, 657-8501, Japan

Masaomi Teshigawara

Division of Environmental Engineering and Architecture, Graduate School of Environmental Studies, Nagoya University, Nagoya, 464-8603, Japan

Wataru Gojo & Yoshinobu Hirano

National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport (NILIM, MLIT), Tsukuba, 305-0802, Japan

Taiki Saito

International Institute of Seismology and Earthquake Engineering, Building Research Institute, Tsukuba, 305-0802, Japan

&

Hiroshi Fukuyama

Department of Structural Engineering, Building Research Institute, Tsukuba, 305-0802, Japan

Abstract: *This article proposes a new framework for performance-based design (PBD) of building structures. This framework was proposed under the 3-year Japanese Government Comprehensive Research and Development Project on "Development of a New Engineering Framework for Building Structures" launched in the fiscal year of 1995. The primary objective of the project is to create a system in which the performance of buildings is clearly stated, and consumers, that is, occupants, are well informed of how their buildings will perform and how much it will cost to maintain their performance. The framework emphasizes the establishment of target performance, the performance evaluation, and the performance statement as the main three elements. It also stresses that an institutional framework and support systems need to be provided to enable PBD to be practiced efficiently. The implementation of the proposed framework is also expected to promote engineering innovation, progress in building engineering, and globalization. The new framework will also bring other benefits, such as improved design techniques, greater design flexibility, and international harmonization. It is also important for building structural performance to become one of the most important indexes for consumers to define a building's value. The Japanese building code was changed to the*

*To whom correspondence should be addressed. E-mail: *fujitani@kobe-u.ac.jp*.

performance-based code, based in the clear and comprehensive manner proposed in this article. In the United States, "Vision 2000" (SEAOC, 1995) was published, then many research activities were conducted simultaneously.

1 INTRODUCTION

In recent years, building owners and occupants have begun to demand an increasing variety of building performance, such as safety, comfort, less expensive to live in, and ease of maintenance. On the other hand, structural technologies for buildings are rapidly advancing, and new materials, structural systems, and design methods are being developed to realize various target performance in building structures. Also, conventional structural technologies should be re-examined in the light of the performance concept. Thus, for re-organizing structural engineering for buildings, we now need a conceptual framework based on performance, in which the performance requirements of buildings are clearly stated and the measures to achieve them can be selected in a discretionary manner.

In 1995, the 3-year Comprehensive Research and Development Project "Development of a New Engineering Framework for Building Structures" was started to develop design technologies for building structures. This project aimed to enable the occupants of a building to understand the performance and costs, and to help them make decisions at the building design stage. A comprehensive committee for the project was established and chaired by Prof. Tsuneo Okada, Shibaura Institute of Technology (Professor Emeritus, University of Tokyo). Three subcommittees were also formed. The Target Level Subcommittee, chaired by Prof. Yoshitsugu Aoki of the Tokyo Institute of Technology, studied methods for understanding demands on building structures and investigated all aspects necessary for establishing target levels. The Performance Evaluation Subcommittee, chaired by Prof. Hiroshi Akiyama of Nihon University (Professor Emeritus, University of Tokyo), conducted studies aimed at evaluating structural performance. The Institutional Framework Subcommittee chaired by Dr. Katsumi Yano of Yano Architectural Consultants, investigated a suitable institutional framework and support system including technological tools, customs, and structural practice to enable the structural engineers to efficiently carry out their jobs in the new framework.

2 OBJECTIVES

The conventional method that is widely used in building design is based on specification criteria rather than performance criteria. These criteria do not state the required building performance such as earthquake resistance. Although it is difficult to predict external forces (such as earthquake) that may act on buildings, building structural technology without a clear statement of required performance is not a modern technology. Without statements of performance, occupants cannot select buildings on that basis, and cannot use market principles to choose those offering lower cost and better performance. Figure 1 shows the concept of the new framework.

The new framework (Okada et al., 2000) aims to help occupants understand performance and costs, to help engineers design and develop new technologies, to preserve international harmonization, and to establish a suitable

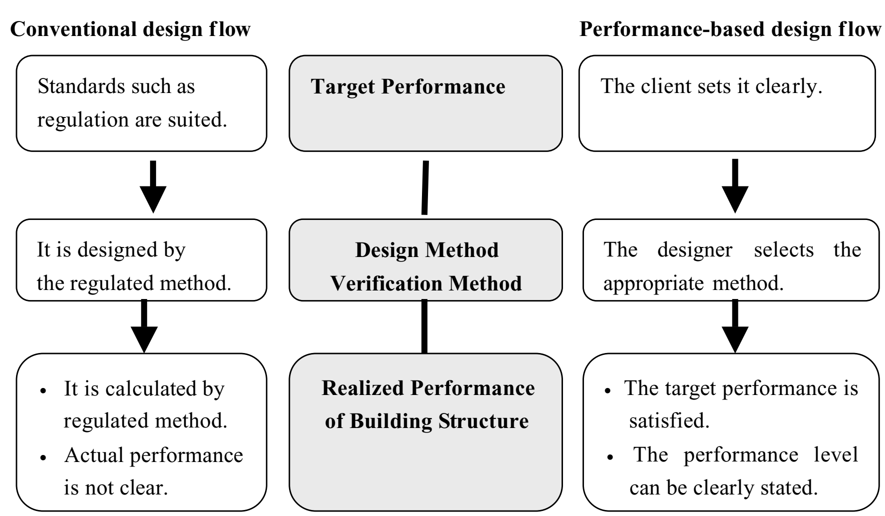

Fig. 1. A comparison of the conventional process and the new process of building structural design.

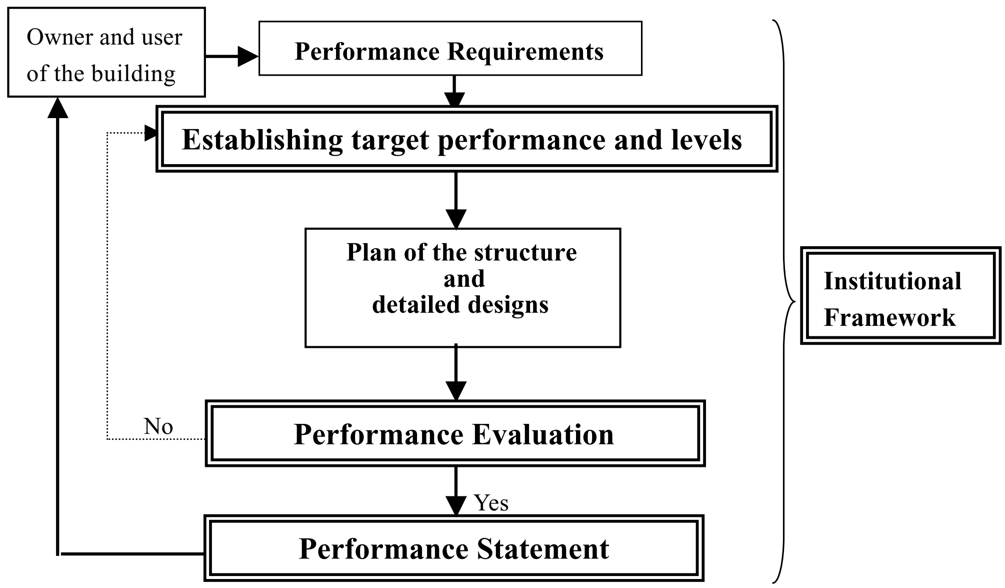

Fig. 2. Design flow chart for a building structure in the PBD system.

Note: This chart illustrates only the flow of PBD. The quality control of construction works and maintenance should be considered separately.

institutional framework which helps market principles function in the economic world that surrounds building structural technology. Performance statements allow various structural systems and materials to be used, and should promote the development and introduction of new technologies and the concept of cost performance. For this purpose, the following three main issues were studied in the project.

To examine the issues related to the target performance levels in structural design, the Target Level Subcommittee was formed in the project. A framework for determining levels, which consists of the fundamental ideas concerning target levels, and various factors that may be used for deciding levels and those used in actual evaluations, was proposed (Aoki et al., 2000).

To examine the issues related to the structural performance-evaluation system for buildings, the Performance Evaluation Subcommittee was organized in the project. A framework for establishment of target performance, verification of performance, and statement of the evaluated performance was proposed (Akiyama et al., 2000).

To examine the issues related to the new institutional framework and support systems, the Social System Subcommittee was formed in the project. A new "Social System," which is composed of various supporting devices for (PBD) practice, such as codes/rules, institutions, technical tools, information systems, etc., was proposed (Yano et al., 2000).

3 OUTLINE OF PBD SYSTEM FOR BUILDING STRUCTURES

The Comprehensive R&D Project proposed a new PBD framework for building structures. The design flow chart is shown in Figure 2. The new framework based on performance consists of basic elements such as "establishment of target performance and levels, performance evaluation," and "performance statement." The design process is conducted in the following steps:

Step 1. Clarify the performance requirements based on the purpose of the building, and establish the target design performance and levels.

Step 2. Adopt design methods that are adequate for attaining the target performance, and decide the frame, materials, and so on.

Step 3. Appropriately evaluate the performance of the designed building structure, and state its performance.

To clarify performance requirements and establish target performance and levels, the public needs should be considered. A building structure, which may be privately owned, always has some sort of public significance and may affect the public. Building structures in cities have their own roles determined by their usage, and should satisfy those roles. Owners and designers should understand the roles that a building should play with the public under certain circumstances.

Structural designers then plan the structures (structural frames and materials) for achieving the established target performance and levels. For example, to attain the target earthquake resistance of structural frames, designers investigate whether the frames resist the energy and force of an earthquake or whether a device should be used to resist or control them, and select detailed methods. Because structural specifications are fundamentally decided by designers' discretion in the new framework, new building structures, devices, and technologies are developed. Design techniques and methods for step 2 should be adopted by each structural designer based on the properties of the building structure.

Structural designers plan the details and prepare blueprints and specifications. Structural plans are evaluated in terms of performance based on the drawings and specifications before construction starts.

Performance is stated when the evaluation shows that the designed building structure satisfies the target performance and levels. Performance statements, which link the occupants of buildings and designers, should be easy for general people to understand. A clear statement of performance is the responsibility of the designer under the new framework, which establishes the reputations of and increases the demands on designers. Those designers who explain a building's performance to the public and provide the performance demanded by the owner at a reasonable cost will be highly regarded.

The institutional framework and support system are needed to ensure efficient operation of the new framework. These should include technological tools, customs, and structural designer's practice.

4 ESTABLISHMENT OF TARGET PERFORMANCE AND LEVELS

4.1 Concept of basic framework for establishing target levels

Building structures must have various kinds of performance criteria, such as safety and serviceability. The performance and levels appropriate for a building are established not only in terms of structural technologies but also by the requirements of its owners, users, and the public. The conventional building-design system has included no definite method or idea for establishing target performance or levels. Although occupants should correctly understand target performance and levels, this has been difficult because technical knowledge is needed to understand structural performance. Therefore, designers are requested to explain these concepts, and to use plain words in public that are easy for the occupants to understand. The Target Level Subcommittee surveyed ideas for determining performance and levels, and conducted various related studies. The subcommittee formed a framework for establishing levels, which is a summary of the fundamental ideas concerning target levels, and investigated various factors that may be used to decide levels and those used in actual evaluations. This section briefly describes the framework for establishing target levels.

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

4.1.2 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 performance 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.

4.1.3 Roles of a building structure and two kinds of demands. A building structure must provide a space in which people feel safe and comfortable. Creation of such a space is the purpose of designing a 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 performance should be understood in terms of (1) private demand and (2) social demands.

4.1.4 Basic framework for deciding target structural performance levels. Even when structural performance 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 damage, and (3) functions that the building is expected to perform 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.

4.1.5 Evaluation indices 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.

4.1.6 Rule for using two or more evaluation indices. Target level to be established under plural evaluation indices should satisfy the below criteria. That is, a target level should be selected when there is no other technically selectable target level, which is evaluated as more desirable than or as desirable as the established target level in all evaluation indices, and also evaluated as desirable in some evaluation indices.

4.1.7 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.

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

The following sections describe the details of examination about each factor in determining structural performance levels.

4.2 Risk level

4.2.1 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. 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 on the society should also be discussed.

4.2.2 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.

4.2.3 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.

4.3 Minimum cost level

4.3.1 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.

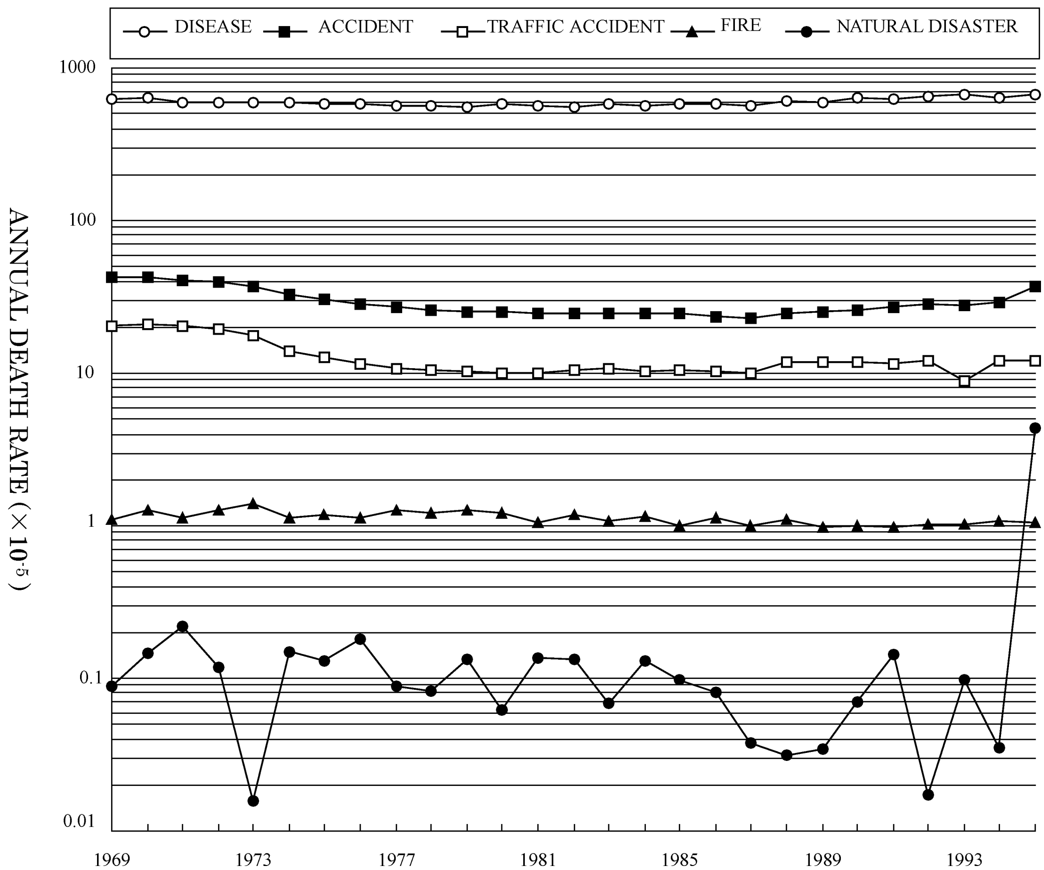

Fig. 3. Annual risks in Japan (1969–1995).

4.3.2 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:

$$C_T = C_I(d) + C_F(d)P_F(d) \tag{1}$$

where C_T is the total cost, C_I is the initial construction cost, C_F is the damage cost, and P_F is the 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 to calculate the expected loss values. The loss by 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 4, the optimum performance level is obtained as the level, which minimizes the total cost.

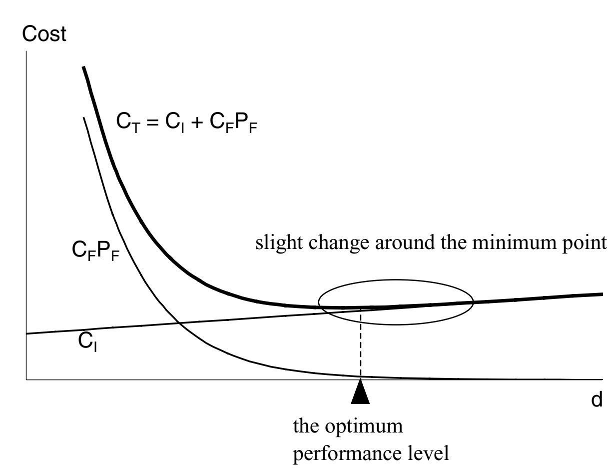

Fig. 4. Principle of minimum total cost.

4.3.3 Characteristics of performance levels that minimize total cost. Simulation analyses 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. As the levels of most existing buildings are within this gentle range, a slight improvement in 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.

4.4 Evaluation of the safety levels

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

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. As 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.

4.4.1 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 factor of building usage or importance factor 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 factor against an earthquake to increase earthquake resistance or by establishing a deformation limit. The study showed that citizens want, and it is economical, 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.

4.4.2 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.

5 PERFORMANCE EVALUATIONS AND STATEMENT

5.1 Concept of performance evaluation and statement

Outline of the structural performance-evaluation system is shown in Figure 5. The flow of the structural performance evaluation in this guideline is as follows: (1) select performance items to evaluate, and establish a target performance level for each item, (2) verify whether the limit state of a building design is sufficient to withstand the load and external forces of various kinds, and (3) write the statement of evaluation for each performance item.

In establishing target structural performance, performance-evaluation items are defined, which are the combinations of basic structural performance (safety, reparability, and serviceability) and an evaluation item (structural frames, building materials, equipment, furniture, and the ground). The basic structural performance aims to protect human lives,

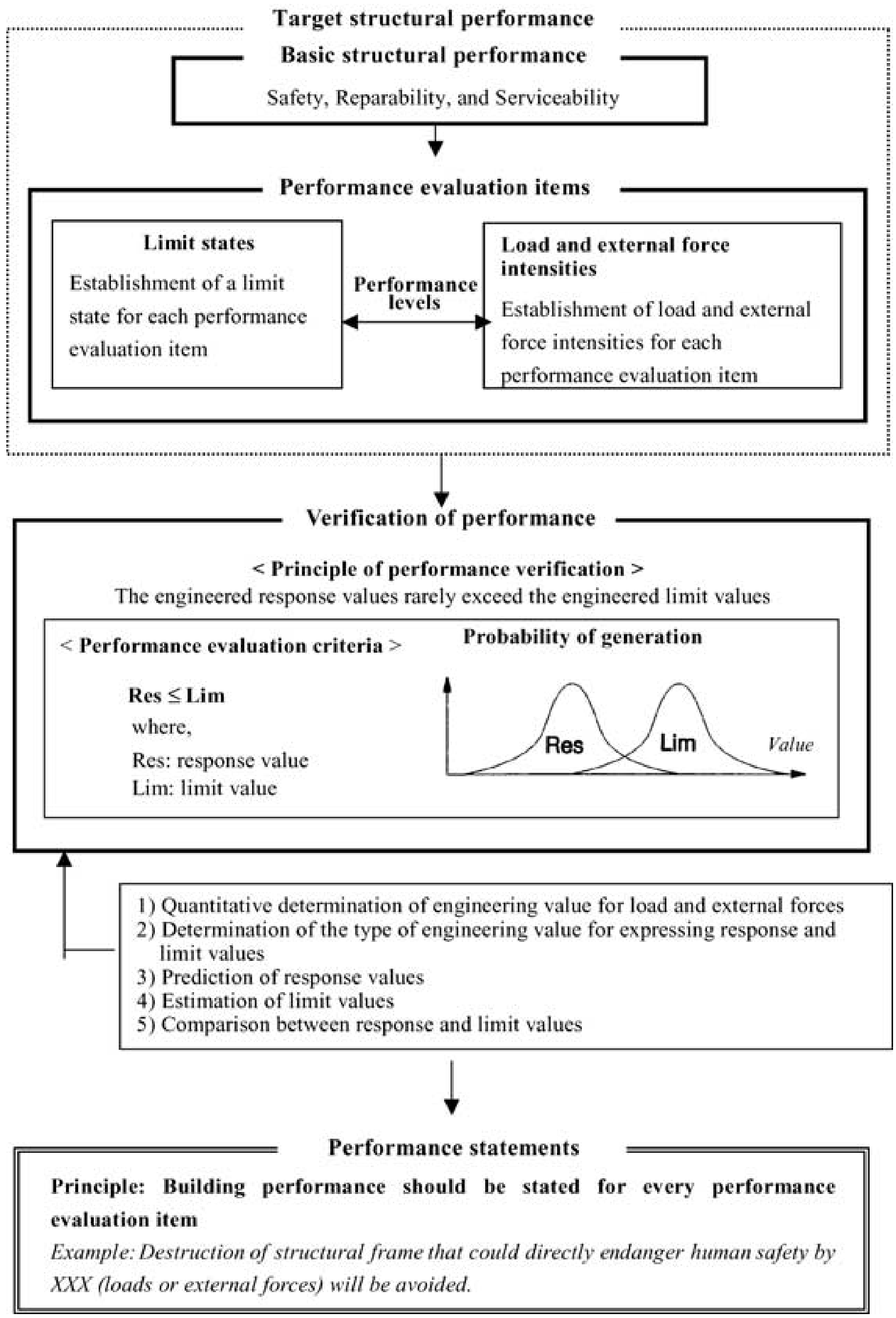

Fig. 5. Structural performance-evaluation system.

property, functions, and comfort, and is used to evaluate a building structure in terms of three different aspects. The target performance level is established for each evaluation item. The performance levels are expressed in terms of the intensity of loads and external forces and the behavior of a building structure when the loads act. The performance-evaluation items and performance items should be concurrently decided by the owner and the designer and must never fall below the minimum levels prescribed by regulations. Performance is verified by predicting the engineering values that show the responses of the building structure (response values) against loads and external forces of various kinds, calculating the engineering values showing the target states

Table 1
Basic structural performance

Safety
Objective: To avoid direct danger to the safety of people in and outside the building (protection of human life)
Evaluation: To prevent the loss of supporting capacity, check the safety of structural frames, building elements, equipment, furniture, and the ground, and adequately prevent their destruction
Reparability
Objective: To ensure the ease of repairing damages caused by external forces to the building (protection of property)
Evaluation: To examine the reparability of structural frames, building elements, equipment, furniture, and the ground, and to adequately control the deterioration and damage within the determined range
Serviceability
Objective: To ensure the functions and comfort of the building (protection of function and comfort)
Evaluation: To adequately remove malfunctions and sensory disorders from structural frames, building elements, equipment, furniture, and the ground

of the building structure (limit values), and comparing these values. The principle is that response values must rarely exceed the corresponding limit values from the engineering point of view.

5.2 Performance-evaluation items

Performance-evaluation items are combinations of five evaluation objects, which are structural frames, building materials, equipment, furniture, and the ground, and three basic elements of structural performance, which are safety, reparability, and serviceability (see Table 1). The performance items to evaluate are those prescribed by law and those selected concurrently by the owner and the design engineer.

As there are many basic structural performance items to evaluate, the items are classified under the five categories described in the above paragraph. Although structural frames and elements have been the main objects of evaluation, this guideline includes equipment, furniture and the ground, the seriousness of damage to which was revealed by the Hyogo-ken Nanbu earthquake in 1995. Structural frames consist of the super-structures and foundation. Although foundations have been treated independently from super-structures, this guideline incorporates the foundation in structures to evaluate the performances of an entire building. Foundations are evaluated as a part of building elements. Building elements are all factors constituting the building structure other than equipment and furniture, and are structural members and interior and exterior non-structural elements. The ground is that which supports the building structure.

These five evaluation objects are not totally independent of each other. The conditions of structural members and the ground should be considered when evaluating structural frames. An aggregate of structural members is the structural frames, and comprehensive evaluation of each element is the evaluation of the structural frames.

5.3 Limit states

The limit states of performance-evaluation items for the basic structural performance, which are safety, reparability, and serviceability, are named safety limit state, reparability limit state, and serviceability limit state, respectively. A limit state is a general term for expressing the state of the requirement for each performance-evaluation item and is defined as a state of a building for expressing structural performance. Limit states for every evaluation item are listed in Table 2. For example, the safety limit state of a structural frame is defined so that the destruction directly affecting human life should be avoided. And in the safety limit of the building element, it is defined such that fall out or scatter of building elements that directly affects human life should be avoided.

The safety limit is judged based on the possibility of direct danger to the life of the people in or outside the construction. Frames must not fall, collapse, or lose vertical supporting capacity. Elements must not fall out or be scattered. Equipment and furniture must not tumble, fall out, or move. The ground must not collapse, degrade, or deform so seriously that the structural frame could be destroyed. The reparability limit is judged based on the degree of damage to the structure and on the ease of repairing and restoring the structure. Allowable ranges are established for every evaluation object. Serviceability limit is judged based on the functions and comfort of the building. Allowable ranges for not causing malfunctions or sensory disorders are established and maintained for every evaluation object. These limit states are thus determined for every performance-evaluation item.

Table 2
Performance evaluation items and limit states

Basic structural performance	*Safety (protection of human life)*	*Reparability (protection of property)*	*Serviceability (maintenance of the functions and comfort)*
Evaluation object		**Limit state**	
	Safety limit	**Reparability limit**	**Serviceability limit**
Structural frames	**Rarely lose the vertical supporting capacity** Structural frames must rarely lose the vertical bearing capacity otherwise human safety may be directly endangered	**Rarely suffer damage exceeding the established range***1 Damage to the structural frames must be within the range predetermined in terms of reparability	**Rarely cause malfunction or sensory disorder** The deformation or vibration of the frames must rarely hinder daily use of the building
Building elements (structural members and interior and exterior non-structural elements)	**Rarely fall out or be scattered** Building elements must rarely fall out or be scattered, otherwise human safety may be directly endangered	**Rarely suffer damage exceeding the predetermined range***1 Damage to building elements must be within the range predetermined in terms of reparability	**Rarely cause malfunction or sensory disorder** The deformation or vibration of the elements must rarely hinder daily use of the building
Equipment	**Rarely tumble, fall over, or move** Equipment must rarely tumble, fall out, or move, not even due to the deformation or vibration of the structural frames or elements; otherwise human safety may be directly endangered	**Rarely suffer damage exceeding the predetermined range***1 Damage to equipment caused by the deformation or vibration of the structural frames or elements must be within the range predetermined in terms of reparability	**Rarely cause malfunction or sensory disorder** The deformation or vibration of the structural frames or elements must rarely hinder daily use of the equipment
Furniture	**Rarely tumble, fall over, or be scattered** Furniture must rarely tumble, fall over, or be scattered, not even due to deformation or vibration of the structural frames or elements, otherwise human safety may be directly endangered	**Rarely suffer damage exceeding the predetermined range***1 Damage to furniture caused by the deformation or vibration of the structural frames or elements must be within the range predetermined in terms of reparability	**Rarely cause malfunction or sensory disorder** The deformation or vibration of the structural frames or elements must rarely hinder daily use of the furniture
The ground*2	**Rarely collapse***3 **or seriously deform***4 The ground must rarely collapse*3 or suffer deformation*4 that may invite the structural frames to lose the vertical supporting capacity, otherwise human safety may be directly endangered	**Rarely suffer damage exceeding the predetermined range***1 The drop of the bearing capacity or the deformation of the ground*4 must be within the range predetermined in terms of ease of repairing the building	**Rarely cause malfunction or sensory disorder** The drop of the bearing capacity or the deformation of the ground*4 must rarely hinder daily use of the building or passage

*1 Damage, drop of bearing capacity, or deformation is in the range determined from the point of reparability (economic and technical points).
*2 Refers to buildings affected by the deformation of the ground, and not the ground itself.
*3 Refers to landslide and the slope failure or lateral flow of banks.
*4 Refers to settlement of the ground, deformation caused by a drop of stiffness (such as liquefaction), cracks, and grade difference.

5.4 Loads and external forces

Loads and external forces that must be considered are the dead load, live load, snow load, wind pressure, earthquake motion (earthquake load), other loads and external forces or disturbances from the ground, temperature, etc. The intensities of loads and external forces used for calculation must be larger than those prescribed by law and should be appropriate for the performance levels of the building and the assumed frequencies of the loads and external forces during the service life of the building. Load frequencies caused by regional and environmental conditions should be considered.

Very rare loads and external forces are usually used in the verification of safety. Rare loads and external forces are used for verifying reparability, and frequent loads and forces are used for examining serviceability. As explained in the above section, the owner and structural designer according to the use and importance of the building should concurrently decide the frequencies of loads and forces. The minimum frequencies prescribed by code must be obeyed. The intensity of loads and external forces should correspond to the structural and functional levels, and may be determined by directly evaluating the frequencies of loads and forces during the service life of the structure. Basic load and external force intensities may be established for assumed frequencies, for which exchange factors are determined.

5.5 Performance verification

Performance verification should be conducted to check whether the responses are reached at the limit states according to the principle of performance verification. Here, the principle of performance verification is that the engineered response value, which expresses the response of a building or a part of a building caused by load and/or external forces should scarcely exceed the engineered limit values, which is a threshold value expressing the corresponding limit state. The performance level is, thus, represented by the quantitative engineering value. The performance verification is conducted according to the following steps.

5.5.1 Quantitative determination of engineering value of loads and external forces. Quantitative values of loads and external forces are determined according to the technical materials related to the background and the setting method of engineering values of loads and external forces.

5.5.2 Determination of the type of engineering value for expressing response and limit values. Suitable types of engineering value for response and limit values should be determined for performance verification. Not only force, but displacement, energy, and acceleration, velocity, etc., can be selected for verifying the structural performance. It means that structural performance is defined by engineering values.

5.5.3 Prediction of response values. The response value that represents the response state should be calculated by the suitable analytical method according to the technical materials describing how to calculate the response value.

5.5.4 Estimation of limit values. The limit value, which represents the limit state, should be established or calculated according to the technical materials described by the quantitative determination method of limit states as limit values. The limit value is the engineering expression of the required building state.

5.5.5 Comparison between response and limit values. The response value should be compared with the limit value for performance evaluation according to the principle of performance verification. The principle of performance verification defines that response value should scarcely exceed limit value from the viewpoint of engineering judgment. This is a criterion for performance verification considering the variation of these engineered values as shown in Figure 5 caused by uncertainties in the determination of load and external forces, in response prediction, and in limit value estimation. The verification methods should be improved and technologies should be developed, but it is still difficult to choose adequate probability targets or design factors. Engineering judgment may be conducted by taking the concepts of performance verification into account.

5.6 Performance statement

Finally, performance of the building should be stated clearly for every performance evaluated based on the principle of performance evaluation. The results of structural performance evaluation and the assumed conditions used for the evaluation should be noted in the statements. Performance statements that can be understood by the general public should also be made.

6 INSTITUTIONAL FRAMEWORK

6.1 The three phases of structural design-related information

Performance-based design practice can be defined as "an act or process to convert one phase into another among the three phases of design-related information: 'Design Brief,' 'Design Criteria,' and 'Design Solutions.'" The information on structural performance in each phase can

Table 3
Three phases of design-related information

	Typical contents	*Information on structural performance*
Phase 1: Design brief	1. Clients' needs and expectations Safety/security levels & quality Market value/utilities, etc. Budget, term of work 2. Social requirements Laws, bylaws, customs, etc. 3. Site conditions, characteristics of the area, etc. 4. Policy of the designer, engineer, and/or the organization	Requirements for structural performance 1. Needs and expectations for structural performance Safety level Security level (damage, property, cost of repairs, etc.) Quality level of structure (prevention of crack, etc.) High market value/utility (e.g., security of household goods, sustainability of business, etc.) Reasonable cost of management (e.g., insurance premiums, maintenance & management costs, etc.) Reasonable construction cost, etc.
Phase 2: Design criteria	1. Basic policies for architectural design, floor and spatial plan, disaster prevention plan, equipment, and environmental plan, etc. 2. Target of each design/plan item 3. Target cost/term of work	Design criteria for structural performance 1. Target performance for structural performance Setting up design criteria using indices (e.g., response value), which are technically measurable 2. Basic policies for structural planning, performance verification, etc. Structural planning: to be developed originally or selected from the menu, etc. Performance verification (methods, verification criteria): to be developed originally or selected from the menu, etc.
Phase 3: Design solutions	1. Plans (floor & spatial plan, architectural plan, structural plan, equipment plan, etc.) 2. Specifications 3. Other information to be transmitted	Design solutions for structural performance 1. Structural plan (various plans) 2. Specifications Materials, construction method, etc. Required ability (workmanship) Specifications for quality control, conditions for supervision, etc. 3. Various information to be transmitted Questions and answers, notification table for design intention, notification table for design quality, etc.

be defined as shown in Table 3, and is converted from one phase into another by performance-based structural design practice.

6.2 Classifications of performance-based "structural design practice"

The process for performance-based "structural design practice" is greatly affected by the conversion forms as well as the "judgment grounds" on which conversion is based. Based on the differences in the "conversion forms" and the "judgment grounds," performance-based "structural design practice" can be classified into some groups.

As examined above, performance-based "structural design practice" can be classified into various patterns. Among possible combinations, the following are the three major patterns (see Table 4).

Note that the classifications listed below represent only typical patterns, and actual "structural design practice" generally lies somewhere in between the three patterns, or it may be a mixture of them. Also, even in relation with the same building, different patterns may be adopted for different parts or different performance items.

6.3 Targets of the "new social system" for performance-based "structural design practice"

6.3.1 The roles of the new system. As a result of the analysis concerning the performance-based "structural design practice" stated above, the following four points should be the main roles expected of the new social system (institutional framework and supporting system).

The following three are those mainly provided to a client in the process of "structural design practice," while

Table 4
Three typical types of performance-based "structural design practice"

Type A: "Individualized objective-oriented" type	As for the "target performance items," those, which are unique to the project concerned, are set up. As for the method for "performance verification," a unique one is selected or developed and applied. As for the "structural planning," an original technique is developed and applied
Type B: "Standardized verification method" type	As for the "target performance items," those found in the menu are selected. As for the method of "performance verification," one method is selected/applied from the menu available. "Structural planning" is executed within the applicable range of the previously selected verification method
Type C: "Dependent on deemed-to-satisfy solutions" type	In the menu for "construction methods" (which give examples of solutions in a prescriptive manner), the one, which is most likely to satisfy the contents and items defined in the "design brief," is selected. Unlike the other types, "structural planning" and "performance verification" are not carried out

the last one (Section 6.3.1.4) is to be provided mainly to a structural engineer.

6.3.1.1 Offering support to clients to clarify the "requirements (needs and expectations)" of structural performance

With respect to a client's "requirements (needs and expectations)" about structural performance of a building, it is necessary to establish some sort of system which can help a client to precisely understand the relationship between his "structural performance requirements" and the "effects and values" which his requirements would add to his building. (Or, in other words, the "demerits and risks" which would be brought about by not requiring any structural performance.) This process can help a client to clarify his "requirements (needs and expectations)" of the project.

Elements constituting the system are, for example, as follows.

(a) A market-system where structural performance levels and social/economic values are linked.
  - Insurance system whose premiums are determined taking the level of structural performance into consideration.
  - A system of structural performance evaluation, which is connected to market value of the building.

(b) A system, which can help a client to further understand "structural performance" and its relating "effects and values" (or "demerits and risks").
  - The methodology and auxiliary tools, which can secure the provision of professional services (in particular, a methodology which can secure the provision of direct or indirect advice by a structural engineer).
  - Information system, which enables a client to judge the qualifications and reliability of a professional who gives him information and advice.
  - Statistical data (e.g., the data concerned with the relationship between structural performance and the market value of buildings, and the correlation between structural performance and the risks of disasters/loss of properties) and other technical information such as minimum performance levels required by society. Communication tools between a client and an engineer including common measures, verification methods, etc. are also necessary.

6.3.1.2 The provision of reliability in converting "requirements (needs and expectations)" into "target performance"

The "requirements (needs and expectations)" of a client for structural performance are clarified and consolidated through communication with a structural engineer. Then, they, together with other given conditions, are converted into "target performance" through technical interpretation and appropriateness examinations by the engineer, and finally they are established as "design criteria," which the structural design details, namely "design solutions" must achieve.

Since such technical interpretation is carried out on a highly sophisticated engineering basis (especially when design practice type is "A" in Table 4), it is generally very difficult for a client to perfectly understand what is going on. Therefore, for a client to be assured that the engineer's conversion results are reliable and that the output ("design criteria") can be used as the basis for the next stage of structural design practice, some sort of system which helps the engineer and client to reach an agreement should be established. The following are some examples of the elements, which constitute the system:

(a) The methodology and auxiliary tools which provide the grounds for judging whether the conversion processes by an engineer were performed in a manner/method that could secure the appropriate output, and/or provide other grounds for judging whether the output of his work is appropriate with respect to its purposes. (In particular, it is important to provide the grounds for judging whether the technical tools used by the engineer are appropriate, he has enough judging ability, he does not misunderstand the facts, or he does not intentionally neglect the conditions, etc.)

(b) The methodology and auxiliary tools required to help all the persons concerned reach an agreement on the converted "target performance" as part of "design criteria" and lead the structural design practice to the next stage.

(c) Information on the professional abilities and competence levels of engineers/organizations, which is necessary to apply the above-mentioned methodology and auxiliary tools.

(d) Evaluation and certification services by an independent body that accredit appropriateness of the technical methods or pertinence of the grounds which were used for conversion or judgment.

6.3.1.3 The provision of reliability of integrity of "target performance" and "design solutions"

By consulting the previously set "target performance," detailed examinations are carried out on the structural plan and the construction methods. Thus, the proposed "design solutions" are verified as to whether they satisfy the "design criteria" and the "target performance." These processes are carried out by making full use of professional technology and knowledge as well as professional tools, especially when design practice type is "A" in Table 4. To ensure that "potential performance" which is to be achieved by the "design solutions" is closely integrated with not only "target performance" but also the "requirements (needs and expectations)" of a client, these processes are of crucial importance.

Since the management of these processes is carried out on a highly sophisticated engineering basis (especially when design practice type is "A"), it is generally very difficult for a client to perfectly understand what is going on. Therefore, for a client to be assured that the engineer's conversion results are reliable and that the output ("design solutions") can be used as the basis for the next stage (production and construction), some sort of system, which helps the engineer and client to reach an agreement, should be established. The following are some examples of the elements, which constitute the system:

(a) The methodology and auxiliary tools which provide the grounds for judging whether the conversion (structural planning and performance verification) processes by an engineer were performed in a manner/method that could secure the appropriate output, and/or provide other grounds for judging whether the output of his work is appropriate with respect to its purposes. (In particular, it is important to provide the grounds for judging whether the technical tools used by the engineer are appropriate, he has enough judging ability, he does not misunderstand the facts, or he does not intentionally neglect the conditions, etc.)

(b) The methodology and auxiliary tools required to help all the persons concerned reach an agreement on the converted "design solutions" and lead to the production/construction stage.

(c) Information on the professional abilities and competence levels of engineers/organizations, which is necessary to apply the above-mentioned methodology and auxiliary tools.

(d) Evaluation and certification services by an independent body which accredit appropriateness of the technical methods or pertinence of the grounds which were used for planning and verification.

6.3.1.4 Providing a structural engineer with a proper environment for carrying out his job

For a structural engineer to carry out the performance-based "design practice" on a stable basis, a certain system which guarantees the following items must be established.

– He can earn a decent economic return for the level and reliability of his service.
– He can manage the risk, which might arise in the course of his work within the proper limits so that it does not exceed his ability and liability.
– He can obtain support in acquiring the knowledge, the grounds for his judgment, and economic ability (namely, liability for his responsibility).

The examples of the elements, which constitute the system, are as follows.

(a) Methodology and auxiliary tools, which clearly define the role and responsibility of a structural engineer. (To clarify the range of the engineer's responsibility in connection with the contract with a client, to define the engineer's responsibility in connection with other structural engineers, architects, equipment design engineers, the person in charge of construction, product/material suppliers, etc.)

(b) Methodology and auxiliary tools which allow a structural engineer to claim proper level of fees for the service he provides.

(c) Insurance or other support tools to his ability to assume his liability which may arise as he provides his service.

Table 5
Seven key functional system elements of the new social system

F01: Quality assurance scheme for structural design practice and related information managing system (to be provided mainly for design practice type A)

Methodology and auxiliary tools that can provide grounds for judging the reliability of the output of each process, namely, the outputs of "design brief: requirements (needs and expectations)," "design criteria: target performance," and "design solutions: possessing performance," respectively

Methodology and auxiliary tools that can clearly define the information on structural performance which have been agreed and confirmed at each process, namely, the "design brief: requirements (needs and expectations)," "design criteria: target performance," and "design solutions: possessing performance," respectively. Moreover, the methodology and auxiliary tools should be provided as the means for tracing back the relationship and integrity of information, whenever necessary.

F02: Data base of reference, technical information, and technical tools (to be provided for design practice types A, B, and C)

A system for information and knowledge in which reference information is stored and managed. In the management of all other functional system elements, engineers and other people concerned are able to have access to this information and knowledge base whenever they need for technical and professional reference materials, for judgment grounds, for tools for their work, for comparison purpose, etc.

F03: Independent bodies to provide related technical services (to be provided for design practice types A, B and C)

A system which provides evaluation or re-verification by an independent body, with respect to the quality assurance scheme stated in F01, for validity of the work (interpretation, conversion, planning, verification, etc.) done by a structural engineer. The system is also assumed to have a function to determine the reliability of the performance certification service stated in F06, as well as to reduce the risks of engineers when they make judgments and decisions in the course of their work.

In connection with F02, a system, which evaluates and certifies pertinence and reliability of various sorts of technical reference information and technical tools (i.e., performance verification method) is also to be provided

F04: Information system on abilities and qualifications of engineers/organizations and system to support them to develop their knowledge and ability (to be provided mainly for design practice type A, but some part is also available for types B and C)

An information system which helps a client select structural engineer/organization and which also provides information to judge technical/liability abilities of engineers/organizations that constitute very important elements to manage the quality assurance scheme stated in F01 and the standard guide stated in F05.

A system supporting engineers to acquire and/or update their knowledge and technical skills

F05: Standard guide of design practice and model contract documents (to be provided mainly for design practice type A, but some part is also available for types B and C)

A system, which helps to define the range of roles and responsibilities of the structural engineers and other persons concerned including architects, other engineers and clients. It also helps to define the scope of the roles and responsibilities of each structural engineer in charge of different kinds of work. It functions as the set of rules for applying the methodology and auxiliary tools related to the quality assurance scheme and information managing system stated in F01. It also includes the methodology for calculation of fees.

F06: Performance certification service (to be provided mainly for design practice type A, but some part is also available for types B and C)

A system to enable clients to enunciate the performance (i.e., the level and contents) of their buildings, which can be linked with the market value of the buildings including premiums for the insurance scheme that is referred to in F07

F07: Insurance system suitable for PBD practice (to be provided mainly for design practice type A, but some part is also available for types B and C)

Insurance systems such as liability insurance for engineers to support their liability capability, a property (damage) insurance scheme linked with the level of structural performance of a building, and a performance guarantee insurance scheme, etc.

(d) Support to acquire and/or update his knowledge and technical abilities which he may need as he provides his service.
(e) The source of information to acquire and update the knowledge and technical abilities.
(f) Technical information, tools, etc. which he can refer to or utilize in his professional practice.
(g) The services of independent bodies for evaluating and authorizing the characteristics and reliability of technical information and tools.

6.4 Key functional system elements of the new system

The "New Social System" consists of several system elements, each of which corresponds to a particular function that the new system is deemed to perform. These system elements can be classified into seven types (listed in Table 5) in terms of their functions. While the design practice type "A" often needs the full set of system elements listed, types "B" and "C" tend to require fewer elements.

7 CONCLUSIONS

The Comprehensive R&D Project of Japan has proposed a new PBD framework for building structures. This framework is expected to produce the following results:

1. The owner will understand the target performance and levels of the building structure.
2. Designers will easily conduct creative design activities, while ensuring appropriate performance using rational measures. Skilled and capable engineers will be highly evaluated.
3. Technologies concerning building structures will be developed, such as new structural methods and devices.
4. The performance and quality of buildings will be improved.

As a result, the concept of cost-performance is treated in structural engineering by the new framework. A healthy market of building structures will be established by forming agreement on the performance of a building structure, such as safety and comfort, between the owner and the designer and by sufficient understanding of owners on the performance. There is no general method for evaluating performance. Precision varies with the evaluation item. Market principles are starting to function appropriately in the field of building structures. As building structures are increasingly evaluated in terms of performance, better evaluation methods will be developed. Designers should help to develop methods for evaluating performance so that their skills can be correctly judged.

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