A NEW FRAMEWORK FOR PERFORMANCE-BASED DESIGN OF BUILDING STRUCTURES

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SUMMARY

This paper proposes a new structural engineering framework for performance-based design (P.B.D.) 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, i.e. occupants, are well informed of how their buildings will perform and how much will costs to attain 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 P.B.D. 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 about 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 criteria for consumers to define a building's value.

INTRODUCTION

In 1995, the 3-year Comprehensive Research and Development Project "Development of a New Engineering Framework for Building Structures" was started in order 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 framework was developed for understanding the demands on building structures, establishing target performance and levels, and appropriately evaluating and stating the performance. This framework should help to develop future technology, to improve designers' discretion in choosing structural design methods, and to establish international harmonization. A comprehensive committee for the project was established and chaired by Prof. Tsuneo Okada, Shibaura Institute of Technology. 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 the University of Tokyo, conducted studies aimed at evaluating structural

performance. The Institutional Framework Subcommittee chaired by Dr. Katsumi Yano of Nikken Sekkei, 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.

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OBJECTIVES

In recent years, building occupants have demanded an increasing variety of building functions. Many desire buildings that are safe, comfortable, inexpensive to live in, and easy to maintain. Building structural technologies are rapidly advancing, and new materials, structural techniques, and design methods are being developed. Performance-based frameworks, which state the performance requirements of buildings are now needed to flexibly use such new materials and structural design methods. 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 Comprehensive R&D Project. The project was conducted to help occupants understand performance and costs, to help engineers design and develop new technologies, to preserve international harmonization, and to establish a suitable 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.

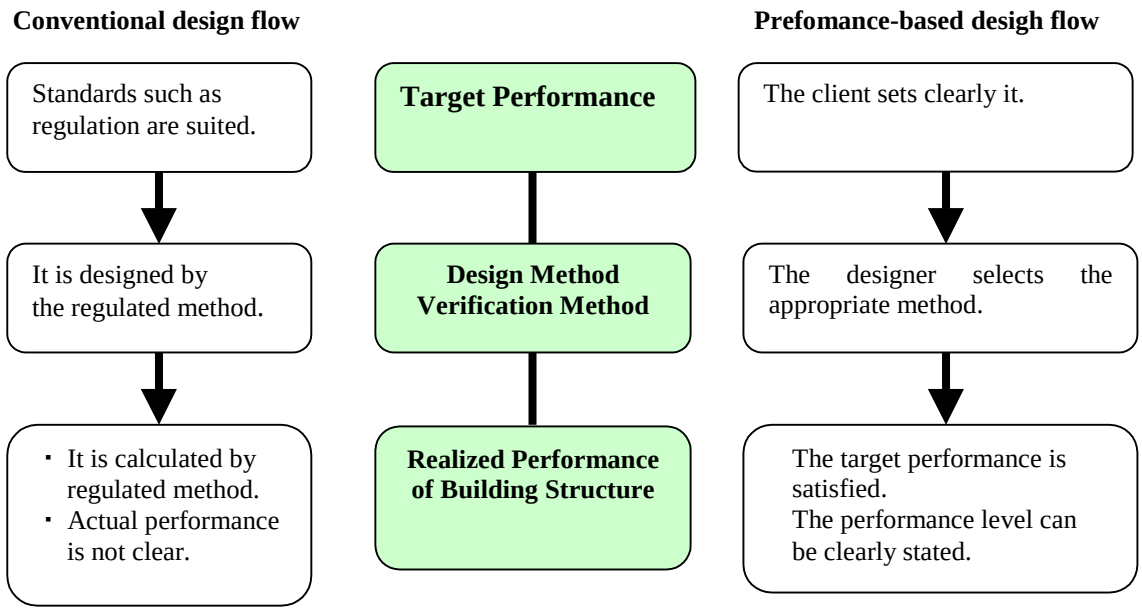


Figure 1: The comparison between conventional process and new process of building structural design

NECESSITY FOR A PERFORMANCE-BASED DESIGN FRAMEWORK

Present states and background

In the present framework in Japan, the performance of building structures have been as follows:

1) Building performance is not stated at the design stage.
Building structures are designed using a predetermined procedure, but without investigating their behavior when a load such as an earthquake groundmotion acts on them and without a statement of required performance. Although the performance that the owners require may not be uniform, they will be dissatisfied because they do not know the performance of what they own. This is caused by the difficulty of estimating loads and external forces, which rarely occur and have complicated properties. The performance of a building structure is usually notable only when such loads or external forces act. The Building Standard Law, other regulations, and technical customs ensure the safety of buildings to a certain degree.

2) It is difficult for occupants to understand the performance.
The occupants receive no explanation and cannot understand the performance of the building structure. The damage to buildings during the Hyogo-ken Nanbu Earthquake in 1995 revealed differences in perspective between consumers and structural engineers. This difference caused public confusion. This is caused by the following. Engineers regard building structures as technical subjects and do not provide occupants with information. Large loads and external forces that test the performance of a building structure are very rare. Occupants are not very interested in this, and there is little demand for performance information.

3) The performance of a building structure is not used to make decisions.
The concept of building performance does not involve market principles. Performance such as earthquake resistance, is used less for selecting a building than plan, exterior and equipment. The concept of cost performance, which is a balance between cost and performance and is dominant in other industrial products, is rarely used in the field of building structures. The fundamental reason for this is that occupants do not understand the benefit they can obtain by paying a certain amount of money, since the performance of building structures are not clearly stated. Building structures have characteristics that are different from other industrial products. Most building structures are produced to order and are unique. Occupants cannot use or examine a building structure before they decide to purchase. In many cases, the owners of buildings are not the users. As a result, the responsibility for an accident may not be clear. Usually, the users are passive about accidents that occur in a place used by many unspecified persons. Therefore, they have believed that they have no control over accidents involving building structures. However, other industrial products are usually both owned and used by one person. For example, automobile accident insurance assumes that the owner or the family of the owner uses the automobile. Vehicle accidents are rarely passive. Even in an accident for which the other person is responsible, drivers often feel that they could have avoided the accident if they had been more careful.

Desirable design system for building structures

First of all, building structures should be designed on the basis of a stated performance, or at least this should be technically possible. In other words, a design framework must be created to determine the behavior of a building structure against loads or external forces that may affect it, to check that the target performance and levels are ensured, and to develop evaluation technologies. In a performance-based design framework, information on building structures should be provided in a form that non-engineers, such as owners, can understand, since the owners should participate in establishing the target performance levels and be responsible for the result. Most other industrial products have descriptions of the performance and consumers use that information to decide whether the product satisfies their needs and to judge the cost performance. Building structures should also be selected in this way. Finally, the building structural performance will be one of the most important measures for consumers to define a building's value. Based on the information provided, an owner judges whether the building meets his needs and objectives on the basis of performance and cost. As a result, the performance of a building structure will be adequately reflected in its value.

OUTLINE OF PERFORMANCE-BASED DESIGN SYSTEM FOR BUILDING STRUCTURES

The Comprehensive R&D Project has proposed a new performance-based design framework for building structures. This chapter outlines this framework, whose 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.

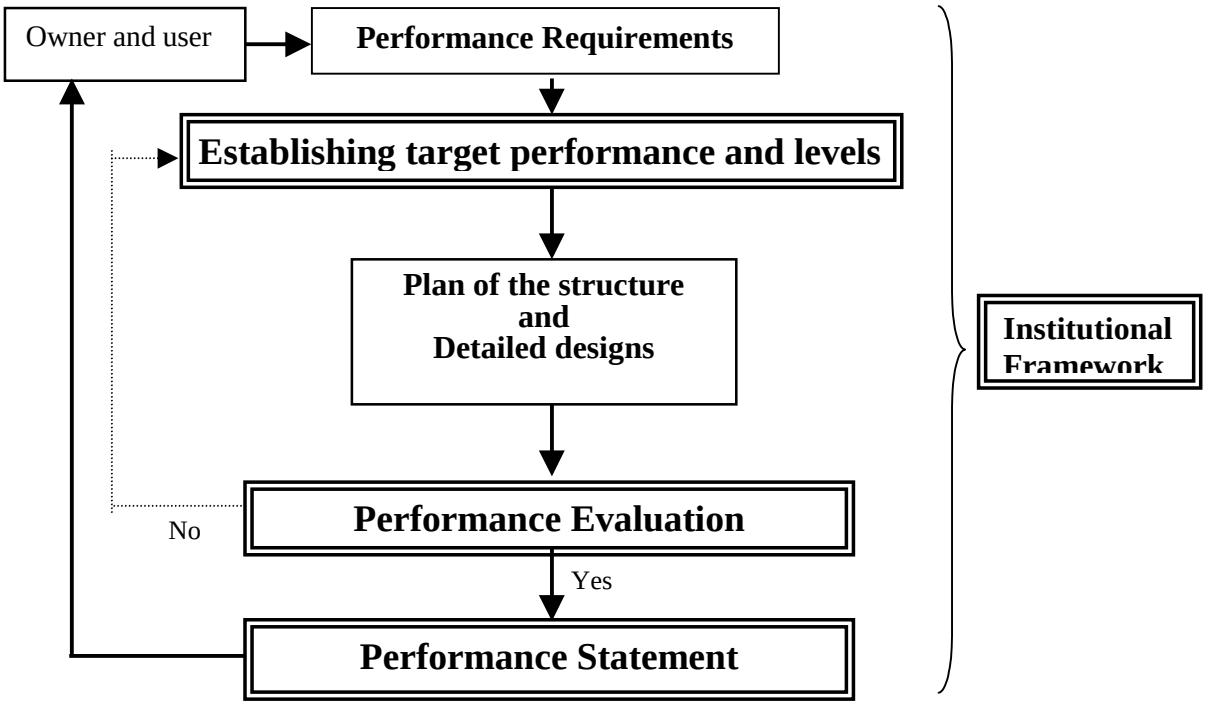
To clarify performance requirements and establish target performance and levels, the public's needs should be considered. A building structure, which may be privately owned, always has some sort of public significance and may affect the public. Building structures in cities have their own roles determined by their usage, and should satisfy those roles. Owners and designers should understand the roles that the building should play with public under certain circumstances. The ideas necessary to clarify performance requirements and establish target performance are described in "Basic framework for establishing target levels"[Aoki et al., 2000]. Chapter 5 outlined the basic concepts.

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. Since 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. The basic factors concerning the entire framework of performance evaluation and statement are described in "The structural performance evaluation guideline (draft)"[Akiyama et al., 2000]. Chapter 6 outlined the basic concepts.

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 reputation 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. The idea of the institutional framework and support system are described in "New institutional framework to ensure efficient operation of new system (draft)"[Yano et al., 2000]. The concept is outlined in the Chapter 7.



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

Figure 2: Design flow chart for a building structure in the performance-based design system

ESTABLISHMENT OF TARGET PERFORMANCE AND LEVELS

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 since 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.

Elements of basic framework for establishing target levels

<Building structural design>
Building structural design is an act of free decision-making concerning building structures. It is a principal part of building design, in which the owner of a building and the designer create a new building space based on their standards for judging a things worth, and its abilities. Since it is a free act, the owner and the designer bear the responsibility for its success.

<Duties of the designer to the owners in structural design>
It is 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 designer to respect the decisions of the owner, cover for the lack of information and technical knowledge, and help the owner to make rational decisions.

<Roles of a building structure and two kinds of demands>
A building must provide a space in which people feel safe and comfortable. Creation of such a space is the purpose of building structural design. Therefore, a building must possess certain degrees of performance to 1) protect human life, 2) conserve property, and 3) maintain functions and other roles that the building is expected to play. In building structural design, performance should be understood in terms of 1) private demand, and 2) public demand.

<Basic framework for understanding target performance levels>
Even when structural performance is understood in terms of engineering values, target levels should be based on personal and public requirements. The levels that should be determined on the bases of the personal requirements of the owner are those concerning 1) human safety, 2) protection of property, including reparability of damage, and 3) daily functions that the building is expected to possess and after being damaged by a certain event. Those that should be considered on the basis of public requirements are 1) safety of users, visitors, and people passing near the building, and 2) the possibility of public loss in terms of damage expansion when the building is damaged.

<Evaluation indexes for establishing target structural performance levels>
There are various factors to be considered in establishing target level. These may be classified into two groups: those that cannot be restored once they are lost, such as human lives and cultural assets (irreparable damage), and those that can be restored under present technical and public systems by repairing, re-construction, or purchasing, although it involves monetary loss (reparable damage). Factors in the latter group are comparable with each other in terms of a single evaluation index: money. However, the former cannot be evaluated in terms of money. Therefore, two or more evaluation indexes should be used in establishing target structural performance levels.

<Rule for using two or more evaluation indexes>
All target levels established with two or more evaluation indexes must obey the following rule. A target level must be selected only when there is no technical alternative that is better with regard to one or more evaluation indexes than the established target level and is the same with regard to all other indexes.

<Probabilistic understanding of phenomena>
All load and resistance phenomena are inherently random in nature. Therefore, they must be understood and quantified in probabilistic terms. The target levels of structural performance should be established on the basis of accepted methods of structural reliability analysis.

<Factors that should be considered in establishing structural performance levels>

1) Performance levels of the building structures whose construction has been based on experience,
2) Risks concerning factors other than structures, and
3) Total cost throughout the life of the structure.

PERFORMANCE EVALUATION AND STATEMENT

Concept of performance evaluation and statement

In establishing target structural performance, performance evaluation items are defined, which are 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, property, functions and comfort; and are used to evaluate a building structure in terms of the 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 of the building structure (limit values), and comparing these values. The principle is that response values must never exceed the corresponding limit values from the engineering point of view.

Framework of performance evaluation and statement

The Performance Evaluation Subcommittee has created a guideline for evaluating building performance, which describes the principles for evaluating whether a building satisfies the target performance and levels. In this framework, safety, reparability, and serviceability are selected as the basic structural performance criteria of a building, corresponding to the protection of human lives, property, functions and comfort, respectively. Basic structural performance is the basic performance required of a building structure to protect people and provide protection from various forces acting on the building and to protect property. Performance evaluation items, which are combinations of basic structural performance and an evaluation object, are then determined. The system uses five evaluation objects: structural frames, building materials, equipment, furniture, and the ground.

Table 1: Performance evaluation items and limit states

Basic structural performance	Safety (Protection of human life)	Reparability (Protection of property)	Serviceability (Maintenance of functions and comfort)

Type of limit state / Evaluation object	Safety limit	Reparability limit	Serviceability limit
Structural frames	Never lose vertical bearing capacity	Never suffer damage exceeding the established range	Never cause malfunction or sensory disorder
Building materials (structural members and interior and exterior materials)	Never fall out or be scattered	Never suffer damage exceeding the predetermined range	Never cause malfunction or sensory disorder
Equipment	Never tumble, fall over or move	Never suffer damage exceeding the predetermined range	Never cause malfunction or Sensory disorder
Furniture	Never tumble, fall over or be scattered	Never suffer damage exceeding the predetermined range	Never cause malfunction or sensory disorder
The ground	Never collapse or seriously deform	Never suffer damage exceeding the predetermined range	Never cause malfunction or sensory disorder

The combinations of one of these five evaluation objects and one of the three basic performance criteria, which are safety, reparability, and serviceability, are called evaluation items. The performance evaluation items and limit states are listed in Table 1. The "Guideline for evaluating structural performance (draft)" advises that performance should be stated in terms of conditions used to establish target structural performance and the results of performance evaluation conducted for each performance evaluation criterion.

INSTITUTIONAL FRAMEWORK

Concept of institutional framework

To adopt such a new structural design framework, which incorporates the requirements of building owners, and to help designers efficiently carry out their work, institutional frameworks that support and act as the base of the system should be established, such as systems, rules, and information. Process models were created to determine the contents of performance-based design. Performance-based design is considered to be the act of converting one of the following three phases to another.

1) Given project conditions (such as requirements of owners and other conditions)
2) Design criteria (such as basic policies and targets in each plan, cost, and construction period)
3) Design solutions, such as blueprints (products of design)

The Institutional Framework Subcommittee has investigated institutional frameworks and rules for storing and using information needed to practice performance-based structural design that can meet the needs of customers.

Functions and roles of institutional frameworks in performance-based design

Institutional frameworks are expected to provide the following four kinds of services to help performance-oriented design:

(Services for customers in each designing process)

1) Help customers to understand their requirements concerning structural performance in terms of effects and costs by providing information and forming related market systems
2) Ensure reliable conversion of requirements to target performance. Customer requirements regarding structural performance and other conditions are converted into target performance and design criteria.
3) Ensure conformity between target performance and design solutions. Structures are designed to satisfy target performance. The resultant design solutions (blueprints) are tested to check whether they actually satisfy the target performance.

(Service for designers throughout the entire design process)

4) Provide good design environments by helping designers to understand their responsibilities in performance-based design and to acquire the knowledge and skills necessary for design, and by providing systems and information that help establish economic conditions.

Vision and direction for an institutional framework for practicing performance-based design

The institutional framework**s** necessary for providing the services described in 7.2 have been further investigated in terms of management and design types and summarized into the following seven systems.

F01) System for guaranteeing the quality of structural design and for controlling information:
Methods and aid tools for showing that the outputs of each principal process are reliable, for stating the contents of decisions and agreements, and, if necessary, for tracing the conformity and relationship between design steps.

F02) Technical reference information, database, and technical tool system:
Database system for reference information and knowledge, which are used as technical and/or design tools for studying, judging, and operating all other systems.

F03) System for independent-body services concerning structural design:
System for independent-body services for providing evaluations by independent bodies or additional services to the F01 system, and for evaluating the appropriateness or the reliability of various technical reference data and tools of the F02 system.

F04) Information system on the skills of structural designers and training system:

System for providing information on technical skills of designers and designer groups and their ability to bear responsibility, which help customers select designers and serve as factors for operating the F01 system. Training system to help designers acquire or enhance their design and technical skills.

F05) Related business standards and a guideline for making contracts:
Systems for clarifying the roles and responsibilities of structural designers and customers, including management rules, such as methods and aid tools for the F01 system, and methods for calculating fees.

F06) System for performance statements:
System for providing information on the contents and levels of structural performance of building on the basis of the results of performance-based design and for connecting the results with the F07 system.

F07) Insurance system:
Designer liability insurance for increasing the ability of designers to bear responsibilities. The subcommittee assumes and proposes systems such as property insurance and performance guarantee insurance both linked with structural performance levels.

CONCLUSIONS

A new performance-based design framework for building structures has been proposed by a Comprehensive R&D Project of Japan. This framework is expected to produce the following results:

1) The owner will understand the target performances 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 develop methods for evaluating performance so that their skills can be correctly judged.

ACKNOWLEDGEMENTS

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