2171

A FRAMEWORK OF STRUCTURAL PERFORMANCE EVALUATION SYSTEM FOR BUILDINGS IN JAPAN

Hiroshi AKIYAMA[1], Masaomi TESHIGAWARA[2] And Hiroshi FUKUYAMA[3]

SUMMARY

This paper introduces the outline of a new framework of structural performance evaluation system for buildings developed by the three-years Japanese national project on "Development of a New Engineering Framework for Building Structures" finished in 1998. The flow of the proposed framework of structural performance evaluation is consists of establishment of target performance, verification of performance, and statement of the evaluated performance. Safety, reparability, and serviceability, which correspond to the protection of human life, property, and functions and comfort, respectively, are provided as basic structural performances for the establishment of target performance. Performance evaluation items, which are combinations of three basic structural performances and five evaluation objects, structural frame, building elements, equipment, furniture, and the ground, should then be determined. Limit states should be prescribed for the every performance evaluation item. Performance levels are expressed as combinations of load and/or external force intensity and limit state. The limit state expresses the condition in which each evaluation object is required to be, in terms of each basic structural performance. 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 building or a part of a building caused by load and/or external forces should not exceed the engineered limit values, which is a threshold value expressing the corresponding limit state. Finally, every estimated performance of the building is stated. The significance of this design system is summarized as: (a) introduction of market principles into the field of structural engineering, (b) promotion of the development of building structural engineering technologies, (c) possibility of the more flexible design, and (d) international harmonization of structural engineering.

INTRODUCTION

The Performance-based structural design system has been developed in the Japanese National Project entitled "Development of a New Engineering Framework for Building Structures." This project has started in 1995 for three years. This paper introduces outline of the "structural performance evaluation guideline" which describes new framework of structural performance evaluation system discussed and proposed in the "Performance Evaluation" sub-committee that is one of the three sub-committees organized under the technical coordinating committee for this national project.

[1] *Graduate school of science and technology, Nihon University, Tokyo, Japan Fax: +81-3-3259-0468*

[2] *Dept. of Structural Engineering, Building Research Institute, Japan E-mail: teshi@kenken.go.jp*

[3] *International Institute of Seismology and Earthquake Engineering, Tsukuba, Japan, Email: fukuyama@kenken.go.jp*

SIGNIFICANCE OF STRUCTURAL PERFORMANCE EVALUATION

The Japanese National Project entitled "Development of a New Engineering Framework for Building Structures" aims to develop a design system in which (a) the owner and the structural designer of a building concurrently decide its performance level, (b) the structural designer suppose appropriate structural system and elements selecting the suitable design and calculation methods, and (c) the structural designer checks whether the building satisfies the established performance level. The system enables flexible, highly reliable structural design by setting only the target performance in the first instance, and allowing engineers to select detail design methods and specifications so as to satisfy the performance level. Although it is obviously necessary to check whether the construction work is executed according to the design, such inspection will not be discussed in this project.

The significance of this design system is summarized in the following three points:

1) Explicit statements of structural performance enable the building owners to freely set performance levels, which must never be below the minimum level prescribed by code, and the structural design of buildings by mutual consent between owners and structural designer. Market principles are thus introduced into the field of structural engineering.
2) The system will promote the development of structural technologies, structural design techniques, advanced materials, and new structural systems to meet performance requirements. New performance based design methods will be developed and proposed.
3) More flexible design will be possible. Structural designers will be allowed to design buildings more freely by selecting structural design techniques that are appropriate for the performance required by the owners.

The new structural design system will also meet the international demand for harmonization of structural design methods.

STRUCTURAL PERFORMANCE EVALUATION SYSTEM

The structural performance evaluation guideline describes the principles for assessing whether a structural design satisfies the target performance level of the building, which are common for every types of building structures.

Flow of structural performance evaluation

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

Target structural performances

Basic structural performances

The basic structural performances are the performances that any building must possess to protect human safety, building functions, and comfort from various forces acting on the building and to maintain the building performance for protection of property. This guideline provides for safety, reparability, and serviceability as the basic structural performances, which correspond to the protection of human life, property, and functions and comfort, respectively, as shown in Table 1.

The purpose of requiring safety is to avoid direct danger to people in and outside the building (protection of human life). Safety verification assesses whether the structural frames, building elements, equipment, furniture, and the ground can avoid destruction or danger to human safety. The purpose of requiring reparability is to secure easy repair of damages caused by external forces to the building (protection of property). Reparability verification assesses whether the deterioration or damage to the structural frames, building elements, equipment, furniture, and the ground is adequately controlled within a predefined range in terms of ease of repair, such as restoration of structural performances, difficulty of repair works, and costs of and economic loss by the repair. The purpose of requiring serviceability is to secure ease of use and living in the construction (protection of functions and comfort). Serviceability verification assesses whether the structural frames, building elements, equipment, furniture, and the ground adequately avoid malfunctions and sensory disorders. These three performances are mutually inter related. The comprehensive structural performance should be improved by coordinating the levels of these functions.

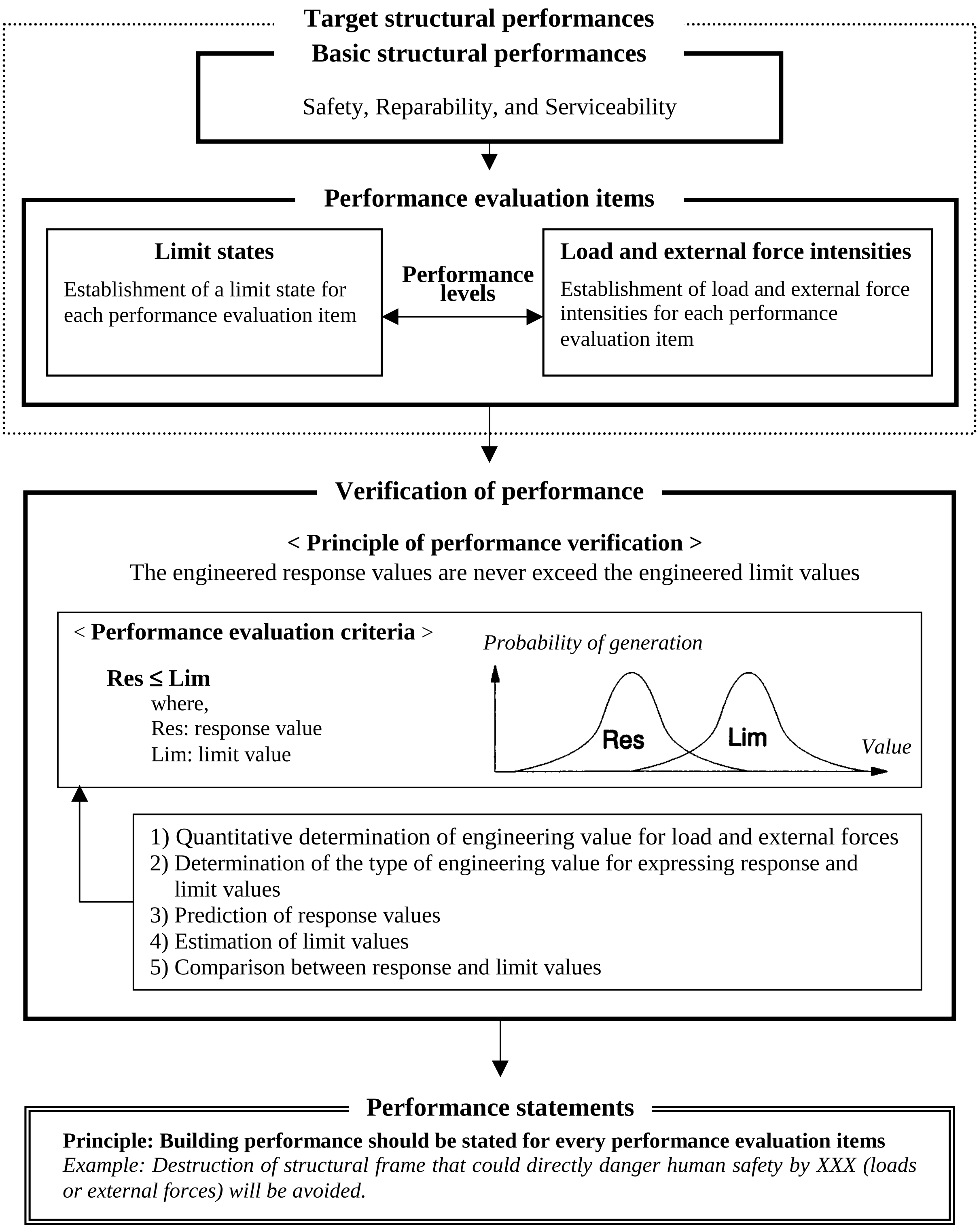

Figure 1: Structural performance evaluation system

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 structural performances, which are safety, reparability and serviceability. The performance items to evaluate are those prescribed by code and those selected concurrently by the owner and the design engineer.

Table 1: Basic structural performances

< 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

Since 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 taking into account 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 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.

Limit states

The limit states of performance evaluation items for the basic structural performances, 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 performances. Limit states for every evaluation item are listed in Table 2. 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 element, it is defined that fall out or scatter of building elements that directly affects human life should be avoided.

Safety limit is judged based on the possibility of direct danger to the life of 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. 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.

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 code 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.

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	**Never lose the vertical supporting capacity** ∗Structural frames must never lose the vertical bearing capacity otherwise human safety may be directly endangered.	**Never suffer damage exceeding the established range***1 ∗Damage to the structural frames must be within the range predetermined in terms of reparability.	**Never cause malfunction or sensory disorder** ∗The deformation or vibration of the frames must never hinder daily use of the building.
Building elements (structural members and interior and exterior non-structural elements)	**Never fall out or be scattered** ∗Building elements must never fall out or be scattered otherwise human safety may be directly endangered.	**Never suffer damage exceeding the predetermined range***1 ∗ Damage to building elements must be within the range predetermined in terms of reparability.	**Never cause malfunction or sensory disorder** ∗ The deformation or vibration of the elements must never hinder daily use of the building.
Equipment	**Never tumble, fall over, or move** ∗ Equipment must never 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.	**Never 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.	**Never cause malfunction or sensory disorder** ∗ The deformation or vibration of the structural frames or elements must never hinder daily use of the equipment.
Furniture	**Never tumble, fall over, or be scattered** Furniture must never 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.	**Never 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.	**Never cause malfunction or sensory disorder** The deformation or vibration of the structural frames or elements must never hinder daily use of the furniture.
The ground*2	**Never collapse***3 **or seriously deform***4 The ground must never 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.	**Never 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.	**Never cause malfunction or sensory disorder** The drop of the bearing capacity or the deformation of the ground*4 must never hinder daily use of the building or passage.

<Definition of terms>

(*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.

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 above section, the frequencies of loads and forces should be concurrently decided by the owner and structural designer according to the use and importance of the building. 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 coefficients are determined.

Structural performance levels

The levels of structural performances of a building should be concurrently decided by its owner and the structural designer and must never fall below the levels, if any, prescribed by code. Structural performance levels are set for each performance evaluation item and are expressed as combinations of limit states and load and/or external force intensities.

The levels of structural performances show the degrees of safety, reparability, and serviceability, and should be concurrently decided by the building owner and the structural designer with consideration of social restrictions and cultural and economic conditions so to satisfy the wishes of the owner. The Japanese Building Standard Law reflects social restrictions and technological levels, and prescribes the minimum levels of structural performances, below which the structural performances of any building must never fall. The factors which should be considered in determining performance levels are the use, importance, and life of the building, the change in load by aging, technical and economic ease of improving performances, the degree of danger to human life, and economic, social, and environmental impacts when the performance evaluation items fall below the minimum level.

An experiential method for evaluating levels should give relative distances from the levels set by the design and damage in the past, the present technical levels, and the minimum levels prescribed by code. With a probability method, evaluation criteria are determined as reliability indices and destruction probabilities, which directly express the degree by which performance evaluation items fall below the determined levels. The structural designer should determine the levels of structural performances, in collaboration with the owner, by comprehensively considering these evaluation factors and criteria. In principle, structural performance levels should be decided by the owner, but the structural designer, who knows structural technologies and performances better than the owner, should play the leading role in determining the performance levels. The structural designer should provide the owner with sufficient information for judging the proposed levels.

This guideline assumes that it is possible to set structural performances at any level requested by the owner. To explain this concept, the performance level of a structural frame against earthquakes is shown in Figure 2. A performance level map (Figure 2 (a)) plots external force intensity (the intensity of earthquake motion) along the Y axis and limit states along the X axis, according to the principle of performance level. The position of the reparability limit point on the X axis is just an example and may be freely established. The (e) and (d) lines correspond to earthquakes of medium intensity, and (c) corresponds to large-intensity earthquakes. The dot C above the serviceability limit point (or above the reparability limit) and the dot C above the safety limit point are the minimum level stipulated by code. Performances are better moving upward and leftward from the line connecting these two dots. The figure shows dotted lines CCC, BBB, and AAA, connecting a serviceability limit, reparability limit, and safety limit. Any performance combinations may be set, such as AAA, AAB, ABC, BBA, BBB, BBC, CCA, CCB, CCC, etc. The load – deflection skeleton curve of structures are shown in Figure 2 (b). Limit states, which were set from various view points, are plotted on the curves, since the load – deflection property of the structure is unique for each building and since the points on a skeleton curve show the states of the structure. The figure schematically shows the envelope curves of three buildings and their response spectra against earthquake motions of (a) to (e). These intersections represent the response of the structures, and the solid curves correspond, from the top downward, to levels AAA, BBB, and CCC in Figure 2 (a). The arrows at the intersections pointing downward represent drops in the load – deflection property. The level may drop from the top curve to AAB or ABC, according to the ductility of the frame, or may rise, like the middle curve that reaches the triangle BBA.

The performance of a structural frame may be set at any level by controlling its load – deflection property. Structural designers will set the property of structural frames according to the performance required by the owners and will design the structures accordingly. In designing constructions to meet performance levels, control of structural frame properties is indispensable. Further technology development is awaited. Figure 2 shows frame performances against earthquakes. Similar diagrams may be drawn for each type of external force and each evaluation object.

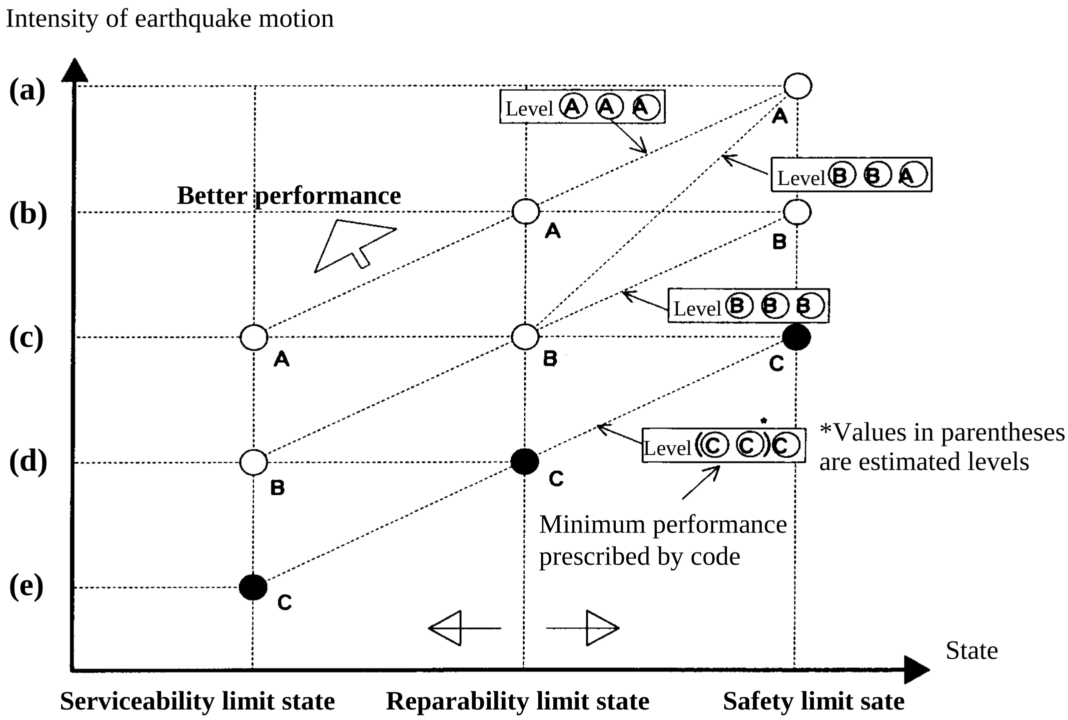

Figure 2 (a): Performance level map

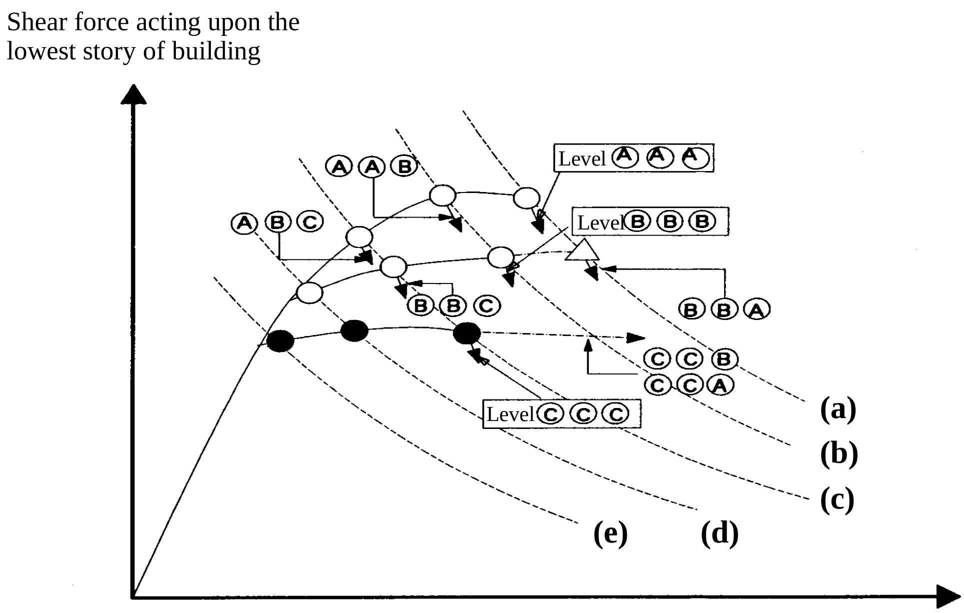

Figure 2 (b): Load – deflection properties and performance levels of structures (against earthquakes)

Figure 2: Schematic diagram of structural performance against earthquakes

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 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 quantitative engineering value. The performance verification is conducted according to the following steps.

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 the background and the setting method of engineering values of loads and external forces.

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 performances are defined by engineering values.

Prediction of response values

The response value which represent the response state should be calculated by the suitable analytical method according to the technical materials described how to calculate the response value.

Estimation of limit values

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

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. Principle of performance verification is defined that the response value should scarcely exceed the limit value from the viewpoint of engineering. This is a criterion for performance verification considering the variation of these engineered values as shown in Fig.1 caused by uncertainties in determination of load and external forces, in response prediction and in limit value estimation. Since it is still difficult to choose adequate probability targets or design factors, engineering judgement may be conducted by taking the concepts of performance verification into account. The verification methods should be improved and the suitable technologies should be developed.

Performance Statement

Finally, performance of the building should be stated clearly for every performances 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.

CONCLUSION

This paper introduces the outline of a new framework of structural performance evaluation system for buildings developed by the Japanese national project on "Development of a New Engineering Framework for Building Structures." The flow of the proposed framework of structural performance evaluation is consists of establishment of target performance, verification of performance, and statement of the structural performance. This framework will promote the improvement of technology on structural performance evaluation. The significance of this design system is summarized as follows: (a) introduction of market principles into the field of structural engineering, (b) promotion of the development of building structural engineering technologies, (c) possibility of the more flexible design, and (d) international harmonization of structural engineering.

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