INTRODUCTION OF A PERFORMANCE-BASED DESIGN

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SUMMARY

The authors have developed a performance based design methodology in which various aspects of seismic performances in buildings are clearly defined. In addition, a “seismic performance menu” has also been prepared to provide common bases for clients and designers in determining design seismic performances of each specific building. The authors have also established technical design targets corresponding to each performance level and the design values i.e., required structural strength levels to satisfy the technical design targets. A series of analyses were carried out on model buildings and it was confirmed that the proposed structural strength levels are efficient in realizing the required performance levels.

INTRODUCTION

Since the 1995 Hyogoken-Nanbu (Kobe) Earthquake, request of clients and the society to clarify various performances, especially seismic ones of buildings is becoming stronger. In order to respond these requests, it is essential to establish a methodology for performance-based design where seismic performances are clearly defined and expressed. Although the authors developed seismic design methodology developed for various building components such as finishes, claddings M&E systems etc., those for structures are focused in this paper.

OUTLINE OF DESIGN METHODOLOGY

Process in the performance-based design

In the performance-based design, a designer has to: clarify the actual performance demand of the client through discussion with them; determine the target performance based on the agreement with them and confirm that results of deign satisfy the target. In addition, there are other activities of designers/consultants after design completion to realize and maintain the required performance. These activities are related to overall design and consulting stages and indicated in Table 1.

Table 1: Process of the performance-based design

Pre-design Stage		
Preliminary Design Stage	Preliminary Design	1) Clarify/confirm clients requirements
	BASIC DESIGN	2) Determine target performance
Design Development Stage	Detail/working Design Design Specification	3) Determine design performance 4) Specify/document design performance
Construction Contract Stage		
Construction Supervision Stage		5) Agree/confirm construction performance 6) Confirm as-built performance
Maintenance Support Stage	Quality Inspection	7) Provide support to maintain as-built performance

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Seismic performance menu

The “seismic performance menu” introduced herein was prepared to identify various levels performance required by clients. The authors classified the seismic performance into 4 categories mainly based on the extent of functions that has to be sustained after seismic actions. 2 levels of design seismic action intensity (EQ level) are defined On the other hand, 3 standard grades (“S”, “A” and “B”) and additional 2 grades (“SS” to represent special use which cannot be classified to ordinary three grades and “E” to represent limited function or safety level) are set forth to give general idea for variation of seismic performances. To each grade and for each EQ level, appropriate seismic performance is assigned. The assignment of performance is indicated in Table 2 and detailed descriptions of seismic performance categories are given in Table 3 together with corresponding predicted or allowable damage level.

Table 2: Seismic performance menu 1

EQ Level Grade of Building	EQ which is predicted to occur several times in the life of the building 80% probability of exceedance in 50 years	EQ which may occur once in the life of the building 10% probability of exceedance in 50 years	Applied use example
SS grade	•keep function•	•keep function•	Atomic power station, etc.
S grade	Keep function	Keep major function	Disastar prevention center, central hospital
A grade	Keep function	Keep limited function	Ordinary hospital, refuge facility, computer center, head office, etc.
B grade	Keep major function	Life safety	Ordinary building
E grade	Keep limited function	-	Temporary buildings

Table 3 Seismic performance menu 2

(Performance level and probable damage)

	Overall	Structure
Keep function	No damage to almost all functions. Almost completely operational at the recovery of infrastructure etc. without repair.	No substantial damage in structural members. No visible residual deformation. **No Damage**
Keep major Function	Damage to prevent main use is avoided. Main functions are operational at the recovery of infrastructure etc. Almost fully operational with slight repair.	No residual deformation to cause structural strength reduction. No repair is requested by structural strength. **Slight Damage**
Keep limited function	Basic functions for occupation are protected. Limited main functions are operational at the recovery of infrastructure etc. Almost fully operational with repair.	Slight loss of structural strength takes place but the building is still capable to resist aftershock. Immediate repair is not needed. **Small Scale Damage**
Life safety	Although the function for the business activity is lost, loss of human life is avoided. The building remains accessible and is available to emergency activity.	Substantial loss of structural strength other than vertical load support capacity takes place. Immediate repair needs may be probable. **Middle Scale Damage**
No guarantee for life safety *	No entry into the building is permitted. Hazardous damage to human life.	Serious damage in structural members. Partial collapse is probable. **Serious Damage**

Remark * This level of performances is to provide explanations for probable damage level when target performance level is not established. It is not intended to be used as one of the design performance level in the practical structural design.

ESTABLISHMENT OF DESIGN PARAMETER

It is necessary to convert prescribed descriptions of performance levels to more concrete explanations of damage levels in order to facilitate common understanding of design performance level. In addition, in the practical design procedure, design parameters have to be clearly identified and their criteria to realize each performance level have to be established. A procedure to identify and establish criteria for the design parameters is shown in the followings for reinforced concrete (RC) and steel reinforced concrete (SRC) structures and for Steel (S) structures separately

Design parameter for damage control of RC & SRC structures

Based on the prescribed definition of performance levels shown in Table 3, damage levels of RC or SRC structural members are defined in detail as shown in Table 4. Criteria for design parameters corresponding to each performance level are shown in Table 5. As the performance levels other than Life Safety are established assuming continuous use or occupancy of the building after earthquake, story drift criteria were introduced so that each plane frame does not reach its ultimate strength. Upper limits of story drift shown in Table 5 were determined referring to ref.1) where limits of the ratio of story drifts to story heights of 1/200, 1/120 and 1/80 are given for serviceability, design and ultimate limit state (for moment resisting frames) respectively.

Image of actual damage level in RC buildings is illustrated in Table 6.

Table 4: Performance level and damage control target of RC & SRC structures

Performance level	Limit of damage in buildings and structural members
Keep function (no damage)	**NO SUBSTANTIAL RESIDUAL DISPLACEMENT.** Maximum crack width is 2 mm which is hardly to find except close observation.
Keep major function (slight damage)	No substantial plastic deformation in main structural members under predicted seismic action. Visible cracks (0.2? 1.0 mm wide) are observed.
Keep limited function (small scale damage)	Most structural members excluding boundary beams do not reach to their ultimate strength. Comparatively large cracks (1? 2 mm wide) are observed but concrete coming out is limited.
Life safety (middle scale damage)	Although the vertical load supporting capacity is maintained, residual displacements or inclinations are observed to adversary affect structural strength. No rupture or partial collapse takes place but some structural members reach to their ultimate strength. Immediate repair is necessary. Formation of large cracks exceeding 2 mm in width on main structural members is observed.

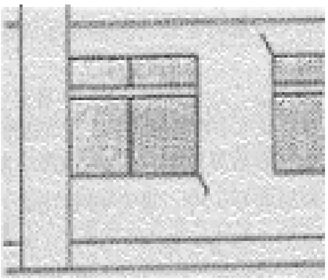
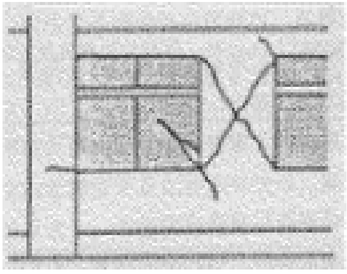
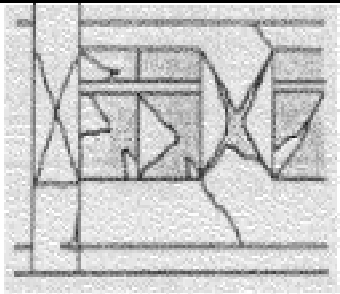
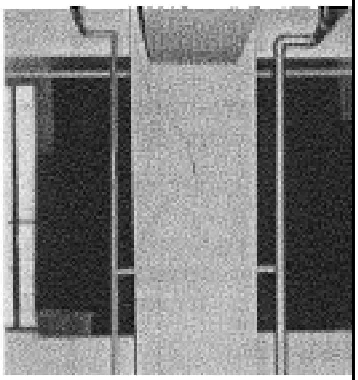
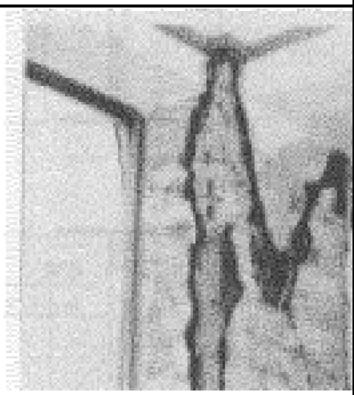
Remark: The crack width criteria shown herein are based on the data in ref.2).

Table 5: criteria for design parameter in rc & src structure

Performance level	Keep functions	Keep major functions	Keep limited functions	Life safety
(story drift)/(story height)•R	where••0.3 •R•1/200 where 0.3•••0.7 •R•1/250 where 0.7•• •R•1/300	where••0.3 •R•1/120 where 0.3•••0.7 •R•1/150 where 0.7•• •R•1/200	where••0.3 •R•1/100 where 0.3•••0.7 •R•1/120 where 0.7•• •R•1/150	where••0.3 •R•1/80 where 0.3•••0.7 •R•1/100 where 0.7•• •R•1/120
Design story shear••u	Not more than yield strength	Not more than ultimate strength	Not more than ultimate strength	No limit
Ductility factor••	••1.0	••1.5	••2.0	••3.0

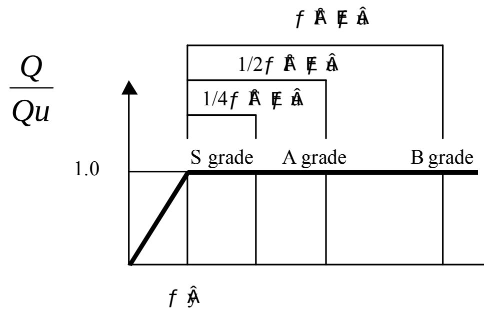
Remark: β□(part of story shear carried by shear walls)□(story shear)

Table 6: Damage level image in RC building

Slight damage	Small scale damage	Middle scale damage
		
		

Design parameter for damage control of steel structures

As the technical parameters to demonstrate ultimate state of steel structures under seismic action, the concept of cumulated inelastic deformation or largest plastic deformation has been proposed. Here, referring to ref.2) etc., a method to control damage in steel structures using cumulated inelastic deformation as the ruling parameter which is illustrated in Fig.1 is proposed.



Cumulated inelastic deformation ratio,ηof frames to the design seismic load is to be limited in terms of that at collapse,•. corresponding the seismic performance grade as follows.

B grade• •••.• •no collapse•
A grade• ••1/2•. •capable of resisting aftershock of the same level•
S grade• ••1/4•. •slight damage only•

Figure 1: Cumulated inelastic deformation concept for damage restriction

According to these criteria, if the frames are highly ductile to demonstrate Ds=0.25, target damage control level is achieved byη<1.9 for S-GRADE and byη<3.8 for A-GRADE.

Based on the above argument, performance level and damage control target for steel structures are shown in Table 7 Design parameters and the criteria corresponding criteria are tabulated in Table 8.

Table 7: Performance level and damage control target of steel structures

Performance level	Limit of damage in buildings and structural members
Keep function •no damage•	Horizontal load carrying structures remain elastic under the design seismic action. No substantial residual deformation or inclination is observed in structure.
Keep major function •slight damage•	Slight plastic deformation is observed partially in structural members but no need for repair. In spite of partial yield in main structural members, the safety factor for collapse prevention is more than 4.
Keep limited function •small scale damage•	Main structures are stressed beyond elastic limit but the safety factor for collapse prevention is more than 2. Therefore, the structure does not collapse if another earthquake of the same intensity occurs.
Life safety •middle scale damage•	Structural members rupture do not take place and even partial collapse does not occur. However, many structural members reach to their ultimate state resulting needs for immediate repair. Visible plastic deformation and local buckling are observed in main structures.

Table 8: Criteria for design parameter in steel structure

Performance level	Keep functions	Keep major	Keep limited	Life safety
(story drift)/(story height) •R	R•1/150	R•1/100	R•1/100	not defined
Cumulated inelastic deformation ratio:•	•• 0	••1/4•$_f$	••1/2•$_f$	•••$_f$

The criteria indicated here are derived on the conditions that each structural member possesses sufficient ductility (plastic deformation capacity) and that seismic energy is not concentrated to parts of the structure. Various appropriate design considerations are essential in designing each structural member to satisfy these conditions. In case that these conditions are not satisfied, criteria suited to each structure have to be developed individually taking into account the actual conditions.

TRIAL DESIGN EXAMPLE

The prescribed design criteria are useful for evaluation of results of design. For the purpose of design, however, more simple and straightforward criteria are preferable. In the following, the level of design ultimate shear force is selected as the representative parameter and critical values to realize each performance level (i.e., seismic grade of buildings) are proposed. By executing time history earthquake response analyses on the model buildings and by comparing the obtained response to the prescribed criteria, it is confirmed that the design based on the simplified criteria is efficient in realizing the target performance level.

Trial design of reinforced concrete building structure

Model buildings as described in 4.1.1 are designed in accordance with 1981 Building Standard Law (BSL) of Japan and the related design standards. Three cases representing B, A and S grades for each model building are considered. In order to realize the target performance levels, B, A and S grade cases are designed to have 1.0, 1.5 and 2.0, respectively, times the ultimate shear strength required by BSL.

Model building

Outline of model building (refer to Figures, 2,3 and 4 for the example of 3 storied model)

Function	•	Office building	Construction site	• Tokyo (site classification 2 of BSL)
Number of stories	•	3,6 and 9 (3 models)	Story height	• 4m (all stories)

Structural system • 2 bays RC moment resisting frames with RC shear walls (dual system) column
in span direc. spacing = 6.0m • and 9.0m (lateral load resisted by shear walls) • (earthquake lateral load)=0.3 • 0.7
in transverse direc. 5 bays RC moment resisting frames column spacing = 6.0 m (for all bays)
Concrete • Ordinary concrete • FC24,FC27(28days compressive strength 24 N/mm^2,27 N/mm^2)
Reinforcement Deformed bar SD345, SD390(D19 • D29) for longitudinal reinforcement SD295 (D10 • 16) for transverse reinforcement
Foundation • In-situ RC pile (tip depth=GL-25m)

4.1.2 Method of analysis

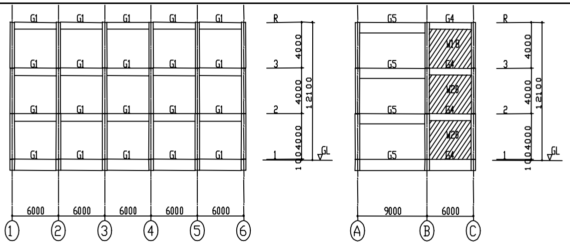


Figure 3: framing elevation (transverse direc.)
Figure 4: framing elevation (span direc.)

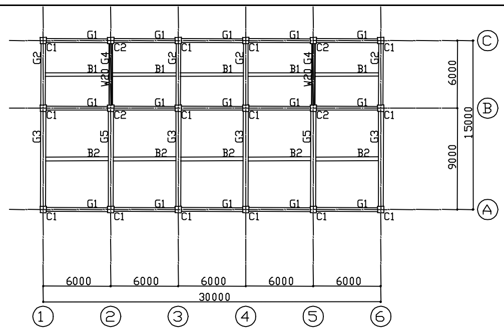


Figure2: floor framing plan

Static • Moment distribution method (vertical load)

Matrix displacement method (lateral load) (elasto-plastic load increment frame analysis for obtaining restoring force characteristics)

Dynamic • Lumped mass (1 mass for each floor) and spring one-dimensional model for each direction

(time history) Restoring force characteristics = • origin oriented type + degrading-model

Input ground motion = artificial wave • 3 waves, each having same phase characteristics as EL CENTRO NS, TAFT EW and Miyagi-ken Oki Earthquake • all with target response spectrum: 1G for short natural period and 80 cm/sec for long natural period (5% damping)

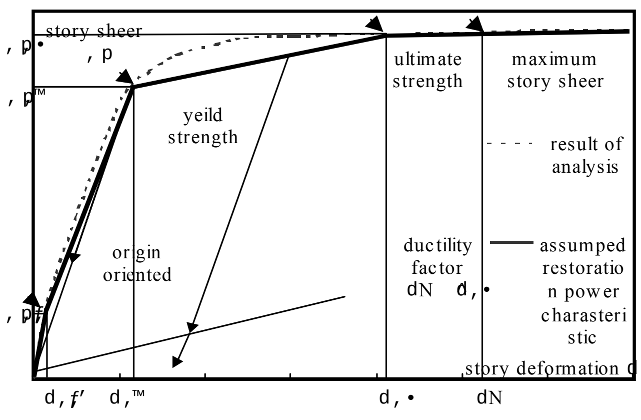


Figure 5: Assumption of the restoration power characteristic

Result of Analysis

Results of response analysis are summarized in Table 9. It is seen that the building structures designed using simplified design target (magnification of ultimate story shear strengths) substantially satisfy the original performance requirements (limit of story drift and response ductility factor).

Table 9: Result of response analysis of reinforced concrete structure building

	Moment resisting frames						Moment resisting frames with shear walls					
Grade	S		A		B		S		A		B	
Stories	1/R	μ	1/R	μ	1/R	μ	1/R	μ	1/R	μ	1/R	μ
3	1/130	1.6	1/110	2.3	1/80	2.9	1/170	1.5	1/150	1.9	1/130	2.1
6	1/140	1.3	1/120	1.6	1/100	2.4	1/130	1.6	1/100	1.6	1/100	2.2
9	1/160	1.3	1/140	1.6	1/120	2.6	1/140	1.1	1/130	1.5	1/120	1.7

Trial design of steel building structure

Same as in case of reinforced concrete structures, model buildings as described in 4.2.1 are designed in accordance with 1981 BSL and the related design standards. In the trial design of steel building structures, B, A and S grade cases are designed to have 1.0, 1.5 and 1.9, respectively, times the ultimate shear strength required by BSL.

Model building

FUNCTION **OFFICE BUILDING** **Construction site** Tokyo (site classification 2 of BSL)

Number of stories 3,6,9 and 12 (4 models) Story height **4M (ALL STORIES)**

Structural system in span direc. Steel moment resisting frames
in transverse direc. Steel moment resisting frames with vertical braces
(lateral load resisted by vertical braces) (earthquake lateral load)=0.3 0.7
Structural steel material specification SN400B (3-story model), SN490B (6-story model), SN590B(9-story model) and SN690B (12-story model)
Foundation In-situ RC pile (tip depth=GL-25m)

Method of analysis

Static• Matrix displacement method (lateral load)
(elasto-plastic load increment frame analysis for obtaining restoring force characteristics)
Dynamic• Lumped mass (1 mass for each floor) and spring one-dimensional model for each direction

(time history) Restoring force characteristics =•normal tri-linear model Input ground motion = artificial wave •3 waves, each having same phase characteristics as EL CENTRO NS, TAFT EW and Miyagi-ken Oki Earthquake• all with target response spectrum:

Analysis result of steel structure

Results of response analysis are summarized in Table 10. It is seen that the building structures designed using simplified design target substantially satisfy the original performance requirements (limit of 1/R and η).
The ratio of cumulated inelastic deformation ratio,ηof B, A, S grade were able to confirm that almost becomes 1:0.5:0.25.

Table 10: Result of vibration analysis of steel structure building

	Pure rahmen structures						Rahmen structures with braces					
Grade	S		A		B		S		A		B	
Stories	1/R	η	1/R	η	1/R	η	1/R	η	1/R	η	1/R	η
3	1/110	5	1/90	14	1/80	23	1/150	19	1/110	27	1/130	41
6	1/100	3	1/100	4	1/100	8	1/180	5	1/150	13	1/130	17
9	1/90	3	1/100	6	1/80	9	1/140	2	1/140	3	1/140	7
12	1/100	1	1/100	3	1/90	7	1/140	1	1/140	6	1/150	10

SUMMARY

The authors proposed a performance-based seismic design methodology to respond a variety of demands of the clients, where various levels of performance design target are clearly defined and described. In addition, a building seismic performance menu was also provided for standard types of building use. Basically, performance levels required only in general or standard types of buildings are explained this menu, the authors believe that it will act as an useful tool to determine design performance in each specific project through communication with the clients.

The authors also presented criteria for selected design parameters corresponding to each performance level target. Although, these parameters are key issues in structural design, it is obvious that more simplified representative criteria are requested in the practical design procedure. The authors selected the ratio of design target ultimate story shear forces to those required by the current Building Code in Japan and carried out some trial design of reinforced concrete and steel structures.

Finally, a series of time history response analyses were carried out. It was concluded from the results of analyses that the buildings designed on the bases of the simplified criteria demonstrate the original target performance levels fairy well.

A seismic design methodology highlighting post earthquake function level of structural finish and other systems was introduced in this paper. However, the post-earthquake performance is not the only one matter to define the total performance. The authors believe a more reliable design methodology to realize integrated performance requirements in buildings can be established taking the concept of life cycle cost and of the risk management into account.

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