Committee Report: JCI- TC084A

Technical Committee on Performance-oriented Seismic Rehabilitation

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Abstract

Seismic rehabilitation that confers high performance such as functionality, restorability, and serviceability, in addition to collapse prevention, during major earthquakes (defined as "performance-oriented seismic rehabilitation") has been increasing in recent years. To meet such performance requirements, new materials, members, and frames, have been developed, and new rehabilitation concepts (response control using seismic isolation or seismic control, and damage control, etc.) have also been introduced.

In view of this situation, the present committee conducted a broad investigation on research, design, and application for performance-oriented seismic rehabilitation, to clarify the current state of the technology.

Keywords: Performance-oriented seismic rehabilitation, research, design, application, building structure, civil engineering structure

1. Introduction

In recent years, concrete structures have begun being seismically retrofitted to give them high-level performance in terms of functionality, restorability, serviceability, and so on, in addition to conventional collapse prevention during major earthquakes. In order to meet such performance requirements, new materials, members, and frames are also being developed, and new rehabilitation concepts (response control using seismic isolation or seismic control, damage control, etc.) are also being introduced. Further, as seismic rehabilitation must be implemented under various constraints caused by the present status of each existing structure, new methods have been developed to overcome diverse constraints. Some examples are technologies that allow work to be done in narrow areas, and technologies that enable rehabilitation while using existing structures.

In view of this situation, this technical committee decided to carry out a study of performance-oriented seismic rehabilitation through a broad investigation of research, design and application in order to clarify the current state of the technology and related issues, while to compile the technical data required for the development and spread of seismic rehabilitation technology.

To this end, the term "performance-oriented seismic rehabilitation" was broadly defined to include rehabilitation methods for overcoming constraints such as the ones mentioned above, in addition to seismic rehabilitation for conferring high-level performance such as functionality, restorability and serviceability, and a broad investigation of these technological trends was conducted. As ten years have passed since the Technical Committee on Evaluation of Seismic Rehabilitation of Concrete Structures6) (abbreviated as "the previous committee") concluded in 2000, the collection of data regarding the characteristics and directions of the technologies that have been developed since then was particularly focused on.

Table 1-1: Committee members

Chairperson	Shunsuke SUGANO	Hiroshima University
Vice Chairpersons	Matsutaro SEKI	The Japan Building Disaster Prevention Association
	Hajime OHUCHI	Osaka City University
Chief Secretary	Hiroshi FUKUYAMA	Building Research Institute
Secretaries	Masaki MAEDA	Tohoku University
	Kenji KOSA	Kyushu Institute of Technology
	Masaomi TESHIGAWARA	Nagoya University
	Susumu NAKAMURA	Nihon University
	Keiji KITAJIMA	Asunaro Aoki Construction Co. Ltd.
	Daisuke TSUKISHIMA	East Japan Railway Company
Members	Akira IGARASHI	Kyoto University
	Kazushi TAKIMOTO	Shimizu Corporation
	Hideo TSUKAGOSHI	Shimizu Corporation
	Takeshi SANO	Obayashi Corporation
	Kiyoshi MASUO	General Building Research Center
	Masaru OKAMOTO	Railway Technical Research Institute
	Shinichi YAMANOBE	Kajima Corporation
	Koichi KUSUNOKI	Yokohama National University
	Mitsuru KAWAMURA	Nihon Sekkei, Inc. (Japan Structural Consultants Association)
	Shigeo WATANABE	Kajima Corporation
	Norio WATANABE	Taisei Corporation
	Hidetoshi SHIOHATA	Nippon Expressway Research Institute Company Limited
	Tsutomu NIINA	Hanshin Expressway Company Limited
	Mitsugu ASANO	Nikken Housing System Co., Ltd
	Masaru FUJIMURA	Takenaka Corporation
	Kazuhiro WATANABE	Urban Renaissance Agency

2. Performance-oriented seismic rehabilitation requirements

2.1 Introduction

Examples of earthquake-caused damage, which led to the focus on "restorability" in terms of high target performance, instead of "collapse prevention," are presented in section **2.2** of this report. Further, requirements besides seismic performance were treated as "constraints to be solved for seismic rehabilitation work." The constraints to be discussed by the committee are listed in section **2.3**, and the definition of "performance-oriented seismic rehabilitation" based on the above is given in section **2.4**.

2.2 Restorability as target performance

(1) Earthquake damage to buildings and restoration

It was reported that a large number of buildings damaged during the 1995 Hyogoken Nanbu (Kobe) Earthquake were demolished, though they escaped from collapse, due to tremendous damage to their structure requiring enormous amounts of money for their repair. It was also reported that the importance of adopting the viewpoint of damage control and restorability was underlined.

(2) Earthquake damage to roads and restoration1)

It was reported that <1> the traffic volume of the Hanshin Expressway, which fell remarkably immediately following the 1995 Hyogoken Nanbu (Kobe) Earthquake, took one year and eight months to return to pre-earthquake levels, <2> not only the costs directly related to restoration incurred, but also the social loss arising from the impossibility of using the expressway were enormous, and <3> the social loss grew in proportion to the length of time required for the restoration of the expressway.

(3) Earthquake damage to railroads and restoration2)

It was reported that <1> although approximately half of the railroad sections that were closed immediately following the 1995 Hyogoken Nanbu (Kobe) Earthquake reopened two days later, it took several additional months to resume service on the JR Tokaido Line, the Sanyo Shinkansen Line, and private railroad lines, particularly between Osaka and Kobe, <2> restoration costs greatly exceeded revenue loss caused by the disaster, and <3> the cost of the resulting social loss reached an enormous level proportional to the restoration period.

2.3 Constraints to be solved during seismic rehabilitation3)

The previous committee, which concluded its work in 2000, studied to propose models and methods for evaluating the seismic performance of rehabilitated members and structures from the viewpoint of strengthening effect, and made recommendations about evaluation systems, etc., that can be applied in common to building structures and civil engineering structures. The last chapter of the report3) presents the results of a questionnaire survey conducted to assemble information about new methods from the viewpoints of <1> the new cases demanding high seismic performance exceeding traditional levels, based on experience from the 1995 Hyogoken Nanbu (Kobe) Earthquake, and <2> the need of performing seismic rehabilitation under diverse constraints according to the present status of each existing structure. **Table 2-1** sums up the constraints to be solved, based on the classification of the purposes of the development of new rehabilitation methods described in this chapter.

The present committee decided to sum up the technologies for the period of about ten years following the conclusion of the work of the previous committee. However, since the constraints to be solved in the seismic rehabilitation did not change during this interval, with on the contrary more closely tailored and sophisticated technology development took place for the same purposes, it was considered to be important to sort out technological trends based on comparison with the data of ten years earlier and use the findings to identify any new issues.

Table 2-1: Seismic Rehabilitation Constraints to Be Solved3)

	Constraint
Building Structure	Short construction period, low cost, reduction of noise/vibration/dust, lighter rehabilitations, reduction of workspace, no need for relocation/moving, design, etc.
Civil Engineering Structure	Short construction period, low cost, reduction of noise/vibration/dust, lighter rehabilitations, underwater work, improved maintenance, construction space constraints, no need for relocation/moving, restrictions on use of fire, water, etc., design, other

2.4 Definition of performance-oriented seismic rehabilitation

Based on the above contents and process, the "performance-oriented seismic rehabilitation" was defined as the "seismic rehabilitation that can "meet the various requirements of society," and it was decided to carry out a study classifying the requirements above into the following two major categories. <1> Securing the target seismic performance (= among the various requirements, those items that are related to seismic performance (see section **2.2**), and <2> Overcoming constraints (=among the various requirements, those items that are not related to seismic performance (see section **2.3**)). The findings of each work group based on this definition are presented in the following chapters.

References

1) Hanshin Expressway Public Corporation, Overcoming Great Seismic Disasters, -Report on Recovery Constructuion from the Disasters-, 1997.9

2) The Railway Bureaw of the Ministry of Transportation, Editorial Committee for Records on Recovery of Railway from the Hanshin-Awaji Great Disasters, Railway revived, 1996.3

3) Japan Concrete Institute, Report of the Task Committee on Evaluation of Seismic Retrofitting Effects, 2000

3. Research on performance-oriented seismic rehabilitation

3.1 Introduction

This chapter presents the results of a survey of the current state of research on performance-oriented seismic rehabilitation for building structures and civil engineering structures, classifying the research into <1> the research on seismic performance evaluation of structures, <2> the research on new seismic rehabilitation methods for various constraints, and <3> other research.

3.2 Research on building structures

(1) Research on performance evaluation of entire building structures

Seismic performance evaluation of RC building structures has been implemented conventionally centering on the ultimate safety during major earthquakes in order to prevent collapse and to ensure the human life. However, in recent years, the importance of continuous serviceability and restorability has become widely recognized, and is now being incorporated in existing seismic standards and performance evaluation methods. An overview is presented here, taking up <1> the "Guidelines for Damage Classification and Recovery Techniques of Damaged Buildings, 2001"1) of the Japan Building Disaster Prevention Association, <2> the "Guidelines for Performance Evaluation of Earthquake-Resistant Reinforced Concrete Buildings (Draft), 2004"2) of the Architectural Institute of Japan, and <3> the "Seismic Rehabilitation of Existing Buildings (ASCE/SEI41-06)"3) of the ASCE. Existing buildings and new buildings are the main focus of all the above standards, however, they can be applied also to rehabilitated buildings as performance evaluation methods.

The Guidelines for Performance Evaluation of Earthquake-Resistant Reinforced Concrete Buildings2) prescribe three limit states, namely serviceability limit state, repairability limit state (2 stages), and safety limit state (**Table 3-1**), and evaluate the seismic capacity of a building in terms of the ratio of the earthquake motion (maximum earthquake motion) that makes the building reach each limit state (**Fig. 3-1**) to the basic earthquake motion. In the case of seismic rehabilitation using seismic control systems, the frame strength index C and the ductility index F remain unchanged before and after the seismic rehabilitation, so the rehabilitation effect cannot be evaluated with the Is (seismic structural index) value in the seismic evaluation standard[5].Therefore, a method[4] to evaluate the rehabilitation effect in terms of the raised Is value using the amplified basic seismic index of structure $E_0=C\times F$ (**Fig. 3-2**), where C is strength index and F is ductility index, corresponding to the increase of energy absorption capacity provided by dampers.

Table 3-1: Limit States in the Performance Evaluation Guidelines of AIJ[2]

Evaluation Item	Limit State	Damage Level	Structural Behavior
Serviceability: Function maintenance	Serviceability limit state	Damage level I	No yielding Residual crack width ≤ 0.2 mm
Repairability: Minor repairs	Repairability limit state I	Damage level II	No cover concrete crushing Residual crack width ≤ 1.0 mm
Repairability: Repairable	Repairability limit state II	Damage level III	No core concrete crushing Residual crack width ≤ 2.0 mm
Safety: Protection of human life	Safety limit state	Damage level IV	No strength loss Maintaining axial force capacity

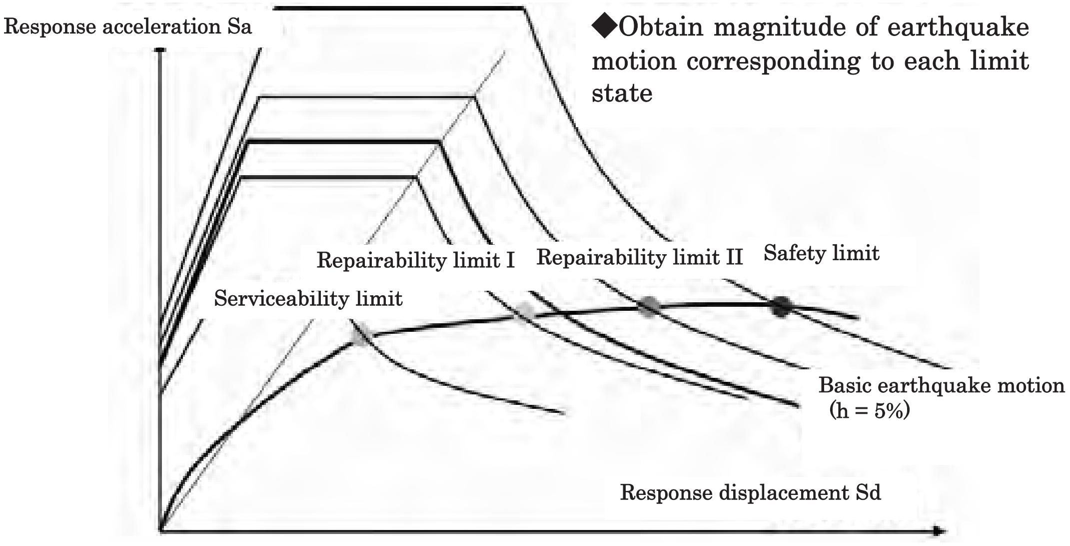


Fig. 3-1: Basic Earthquake Motion and Limit Earthquake Motions Corresponding to Limit States

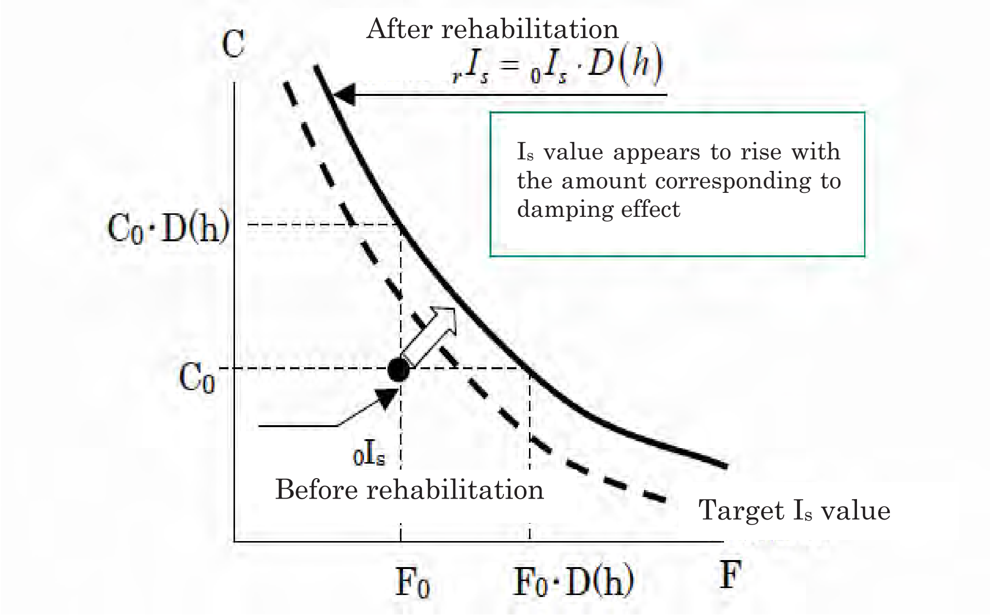


Fig. 3-2: Concept of Is Value Conversion When Seismic Control is Used[4)]

(2) New rehabilitation methods for overcoming constraints

Recently researched and developed new seismic rehabilitation methods and technologies for building structures, namely <1> strength enhancement rehabilitation methods, <2> ductility enhancement rehabilitation methods, and <3> rehabilitation methods using seismic isolation or seismic control were compiled in this section. New seismic rehabilitation methods have been developed for constraints such as the construction using the building and the restriction due to work space and noise/vibration. With regard to the strength enhancement rehabilitation which adds steel braces or RC walls, the adhesive connection method to reduce the use of post-installed anchors, and the external rehabilitation method to allow the work on the exterior side of the building only, were frequently seen. As the new methods of ductility enhancement rehabilitation <1> the method using continuous fiber to jacket members, <2> the method to use non-welded steel jacketing, and <3> the method using polymer cement mortar to jacket members, were seen.

Tables 3-2, **3-3**, and **3-4** list the applicability of the various methods and technologies to overcome various constraints. In **Tables 3-2**, **3-3**, the symbols ◎ , ○ and △ indicate “excellent”, “good” and “fair”, respectively.

Table 3-2: Applicability of Strength Type Seismic Strengthening to Constraints

Rehabilitation Element		Slab			Wall				Connection Type				
Connection Type		S		C	C								
Constraint		H-Section steel	Steel pipe	PCa	RC	Concrete Block General	Concrete Block Special	PCa	Anchors	Bonding + anchors	Partial anchor	Bonding	Prestressing steel bar binding
Structural performance	Structural strength	○	○	○	◎	○	○	○	◎	○	○	○	◎
Construction	Building use during construction	○	○	○	△	○		○	△	○	○	◎	○
	Noise, vibration, dust, and odor countermeasures	○	○	○	△	○		○	△	○	○	◎	○
	Construction conditions	○	◎	◎	△	◎		◎	△	○	○	◎	○
Design	Visual appearance	○	◎	○	—	—	◎	○	—				
				*1				*2					

(Notes)
*1: Steel tube braces excel in terms of visual appearance because they eliminate the need to install buckling restraints.
*2: Special concrete blocks exploit shape and material characteristics, excelling in terms of visual appearance.

Table 3-3: Applicability of Ductility Type Seismic Strengthening to Constraints

Material		CFRP	CFRP laminate	AFRP	Polyethylene tape	Steel plate without welding	Conventional method	
Constraint							Steel place with welding	RC jacketing
Structural performance	Structural strength	○	○	○	△	◎	◎	○
Construction	Building use during construction	◎	◎	◎	◎	◎	○	△
	Work space	◎	◎	◎	◎	◎	○	○
	Light weighting of rehabilitation members	◎	○	◎	◎	△	△	○
	Noise, vibration and dust countermeasures	○	◎	○	○	◎	△	○
	Fire	○	○	○	○	○	×	○
Cost	Construction cost	○	△	○	○	△	○	◎
Construction period	Short construction period	◎	◎	◎	◎	◎	○	○

Table 3-4: Applicability of Response Control Rehabilitation Methods to Constraints

Method / Constraint		Seismic Isolation Rehabilitation		Seismic Control Rehabilitation		Assessment Standard
		Under-foundation isolation	Mid-story isolation	In-frame seismic control	Out of frame seismic control	
Structural performance	Response control performance	◎	○	△	△	◎○: Extremely high △: High
	Rehabilitation of existing frames	◎	○*1	△*2	△*2	◎: Required ○△: Investigation necessary
	Fireproofing	◎	△	◎*3	◎*3	◎: Not required △: Required
	Clearance to land boundaries	△*4	○*5	◎	△*6	◎: Not required ○: Investigation necessary △: Required
	Consideration of earthquake during construction	○	○	◎	◎	◎: Almost not required ○: Investigation necessary
Construction	Workspace for construction	△*7	○	◎	△*8	◎: Not required ○: Partially required △: Required
	Influence on use of building during construction	◎	○	△	◎	◎: No influence ○: Partial influence △: Influence
	countermeasures for noise, vibration, dust and others	◎	○	△	○	◎: Almost not required ○: Somewhat required △: Required
Serviceability	Serviceability after rehabilitation	◎	○	△	◎	◎: No change in serviceability ○: Partial loss of serviceability △: Reduced serviceability
Cost	Construction cost	△	○	◎	○	◎: Low ○: Neither low nor high △: High
	Cost for temporary relocation	◎	△	△	◎	◎: Not required △: Required
Construction period	Construction period for rehabilitation	△*9	△	○	◎	◎: Short ○: Relatively short △: Long
Design	Influence on visual appearance	◎	○	◎	△	◎: Almost no influence ○: Partial influence △: Influence

*1: Seismic rehabilitation of the existing frame below the isolation story may be required.
*2: If existing frames do not have sufficient strength against additional seismic control forces, or if they do not have sufficient ductility, seismic rehabilitation is required.
*3: As the simultaneous occurrence of an earthquake and a fire is considered unlikely, fireproofing of the seismic control damper is not required in most cases.
*4: Clearance is required in order to provide the seismic isolation pits.
*5: The planning that the building may not cross adjacent land boundaries, even if large deformation occurs in the isolation story, is required.
*6: The clearance corresponding to the dimension of externally added frames is required.
*7: The space around the building to bring heavy machines below the foundation is required.
*8: The space to build externally added frames and foundation is required.
*9: This requires long construction period, however, this does not require temporary removal of occupants, and therefore, the constraint is relatively small.

(3) Other research

Among the various earthquake damage surveys conducted in recent years, the case of the behavior of RC rehabilitated buildings during the 2003 Miyagiken-Oki Earthquake was reported. Three RC school buildings that had been rehabilitated using framed steel braces, RC shear walls, and/or column jacketing with steel plate were confirmed not to have suffered major damage, demonstrating the effectiveness of rehabilitation members.

3.3 Research on civil engineering structures

This section explains about the classification of new seismic rehabilitation methods for civil engineering structures. **Table 3-5** lists the categories of applicable constraints, features, and priority levels of rehabilitation methods that have been subjected to construction technology reviews at civil engineering research centers, etc., and/or for which design and construction guidelines have been issued. Main constraints are, for example, the construction of bridges standing in water, and manual construction in a narrow area where heavy construction machines may not be used. Along with an outline of the experiments conducted for each method, the text demonstrated in detail the effects of seismic rehabilitation.

Table 3-6 shows the evaluations of each rehabilitation method for various constraints. In the table the constraints are classified into two groups. One is the group of constraints related to cross sectional dimension and shape of bridge piers and the other is the group of constraints related to relaxation of hard work conditions, such as non-site welding method, short construction period, and underwater construction. The symbols ◎ and ○ used in these tables indicate items that have good applicability under the constraints, and it can be seen that new technologies have been developed for the improvement of specific constraints.

References

1) Japan Building Disaster Prevention Association: Guidelines for Damage Classification and Recovery Techniques of Damaged Buildings, 2001

2) Architectural Institute of Japan: Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings (Draft), 2004

3) ASCE: Seismic Rehabilitation of Existing Buildings (ASCE Standard ASCE/SEI-41-06, 2007)

4) Hiroshi Kuramoto, Masanori Iiba and Akira Wada: A Seismic Evaluation Method for Existing Reinforced Concrete Buildings Retrofitted by Response Controlling Techniques, Journal of Structural and Construction. Engineering, AIJ, No. 559, pp.189-195, 2002.9

5) Japan Building Disaster Prevention Association: Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings, 2001

Table 3-5: New Seismic Rehabilitation Methods for Civil Engineering Structures to Overcome Constraints

No.	Technology Name	Constraint, Features and Priority	Purpose of Rehabilitation
1	Underwater rehabilitation method using precast panels (PRISM method)	Improved durability, site–welding unnecessary, underwater work (no cofferdam required)	Shear, bending, ductility, bar cut-off
2	PCM shotcreting method	Short construction period, even quality, reduced jacketing thickness	Shear, bending, ductility, bar cut-off
3	Steel jacketing using mechanical joints	Underwater work (no cofferdam required), site–welding unnecessary,	Shear, bending, ductility
4	Corrugated split steel jacketing method	Manual construction (narrow area for construction), site–welding unnecessary,, short construction period	Shear, ductility
5	A&P seismic rehabilitation method	Manual construction, site–welding unnecessary, short construction period	Shear, ductility
6	CF anchor	Obstructions, narrow area for construction, site–welding unnecessary, short construction period	Shear, ductility
7	SRF method	Manual construction (narrow area for construction), site–welding unnecessary, short construction period	Shear, ductility,
8	Single-face seismic rehabilitation method	Obstructions, narrow area for construction, site–welding unnecessary, construction from a single face	Shear, ductility, bar cut-off
9	RB (ribbed bar) seismic rehabilitation method	Manual construction (narrow area for construction)	Ductility

Table 3-6: Assessment of Bridge Pier Rehabilitation and Rehabilitation against Constraints

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">Concrete jacketing</th><th colspan="2">Steel jacketing</th><th colspan="3">New material jacketing</th><th rowspan="2">Single-face seismic rehabilitation</th><th rowspan="2">RB seismic rehabilitation</th><th rowspan="2">Seismic isolation / seismic control</th></tr>
<tr><th>PCa panel</th><th>PCM shot-creting</th><th>Mechanical joint</th><th>Corrugated steel plate</th><th>P&A</th><th>CF anchor</th><th>SRF method</th></tr>
<tr><td rowspan="3">Dimension & shape of bridge pier</td><td>Increased section limit</td><td></td><td>△</td><td colspan="2">○</td><td colspan="3">◎</td><td>○</td><td>○</td><td rowspan="3">◎</td></tr>
<tr><td>Narrow spacee</td><td colspan="2"></td><td></td><td>○</td><td></td><td>○</td><td>○</td><td>◎</td><td>◎</td></tr>
<tr><td>Single face construction</td><td colspan="2"></td><td colspan="2"></td><td colspan="3"></td><td>◎</td><td></td></tr>
<tr><td rowspan="3">Construction conditions</td><td>Site welding unnecessary</td><td>○</td><td></td><td>○</td><td>○</td><td colspan="3">○</td><td>○</td><td></td><td></td></tr>
<tr><td>Short period construction</td><td></td><td>○</td><td></td><td>○</td><td colspan="3">○</td><td>○</td><td></td><td></td></tr>
<tr><td>Underwater work</td><td></td><td>○</td><td></td><td>○</td><td colspan="3"></td><td></td><td></td><td></td></tr>
</table>

4. Design of performance-oriented seismic rehabilitation

4.1 Introduction

Seismic rehabilitation is performed as part of lifecycle management to secure the reliability of existing structures that will continue to be used in the future. Section **4.2** describes the “performance matrix”, which combines the "seismic performance grades", which indicate the relationship between earthquake motion level and the state of a structure, with the "state matrix", which indicates the relationship between the state of a structure and its actual engineering quantities. The method to evaluate seismic performance of a structure based on this “performance matrix” is described in section **4.3**, and the method to evaluate seismic performance taking into account also the cost involved in damage recovery following an earthquake is described in section **4.4**.

4.2 Performance matrix

Generally in the seismic design of structures in new construction, an earthquake motion level is set and it is checked that the state of the structure is within the prescribed state. Here, the seismic performance grade, which is a function of the combination of earthquake motion level and structure state, is expressed as "High," "Medium," and "Ordinary." The earthquake motion is classified into two levels according to the length of the recurrence interval: the level 1 (short interval), and the level 2 (long interval), and is expressed in terms of the response spectra taking into account the characteristics (maritime, inland) of the earthquake occurrence mechanism. The seismic waves used for the evaluation of seismic performance using dynamic analysis match these response spectra.

Regarding the states of a structure, “function maintenance“, “limited function maintenance”, “structure maintenance”, “immediately before collapse” and “collapse” are set, and each state is expressed with concrete engineering quantities. The matrix that indicates the performance grade and the state of the structure is referred to here as the “performance matrix”. Examples of performance matrices of building structures and civil engineering structures are shown in **Tables 4-1** through **4-4**. Setting the performance grade of a structure can be done taking into consideration of the lifetime of that structure. The conditions for the level 2 earthquake motion, which is used to evaluate safety, can be given priority while other performance requirements may be relaxed.

There is also a method to express seismic performance in terms of the earthquake motion level (strength) when a structure reaches the prescribed state. The earthquake motion levels differ between building structures and civil engineering structures, and the shapes of the response spectra differ too. The duration time and phase characteristics cannot be expressed by the response spectra, however, it may be possible that the seismic performance is expressed in a unified manner when the seismic performance is evaluated in terms of the earthquake motion level. The possibilities of this evaluation method are described in the following section **4.3**.

4.3 Seismic performance evaluation of structures

It is the principle of seismic performance evaluation of structures <1> to obtain the level of the earthquake motion which makes the structure reach the prescribed state, and <2> to verify that the obtained level of earthquake motion is higher than the earthquake motion level which is prescribed in the “performance grade”, or <3> to verify that the state of the structure remains within the prescribed state under the earthquake motion level prescribed in the “performance grade”.

It is also the principle that the performance is verified using dynamic response analysis, however, static analysis may be used depending on the type of structure. Regarding the modeling of structures, it is necessary to pay attention to the unity of rehabilitation members and existing structures and to the modeling of joints. Moreover, the modeling that adequately evaluates the current state of existing structures is also required. Particular attention is required when evaluating structures that have been damaged.

4.4 Current state of restoration performance evaluation

The method to estimate the restoration cost taking into account the restoration performance was investigated in this section. Examples of the checking of restoration performance of civil engineering structures considering economy were reviewed referring to the technical committee report1) on resiliency evaluation for damaged structures and so on.

Regarding the estimation of restoration cost, <1> an example2) of the framework of the design method based on the restoration cost of the damaged structure and the restoration duration, <2> the method to estimate restoration cost and restoration time (**Fig. 4-1**), and <3> the results of review of research cases3~8) where the effectiveness of seismic rehabilitation was evaluated in terms of the lifecycle cost (LCC) based on earthquake risk management technology, were presented in this section. It is believed that these research cases will serve as reference for the evaluation of seismic performance and LCC of the structure that is seismically rehabilitated with the concept of performance-oriented seismic rehabilitation.

An example of the equation to evaluate the earthquake loss amount required for the estimation of restoration cost is shown in Eq. (4.1). where L(a) represents the earthquake loss amount caused by the earthquake ground motion with the maximum acceleration *a*. The earthquake loss amount L(a) is expressed as the sum of the product of the damage probability F(a) and the repair cost C for each damage level.

$$L(a) = (F1(a) - F2(a)) \cdot C1 + (F2(a) - F3(a)) \cdot C2 + F3(a) \cdot C3 \qquad (4.1)$$

where F1(a) is the probability of minor damage, F2(a) is the probability of moderate damage and F3(a) is the probability of major damage, C1 is the repair cost for minor damage, C2 is the repair cost for moderate damage and C3 is the repair cost for major damage.

In the seismic design of current civil engineering structures, the level 1 earthquake motion considering the restorability of structures and the level 2 earthquake motion considering the safety of structures are set, and the performance of a structure is checked for each earthquake motion. For the level 1 earthquake motion, restorability is checked by maintaining the structure within the elastic range (no damage).

On the other hand, a new checking method of restorability using economy as an index is being proposed instead of the method maintaining the structure within an undamaged state for the current level 1 earthquake motion. The aim of this method is to design structures by minimizing the total cost, which is the sum of the initial construction cost of the structure and the damage cost for all the earthquakes that may occur during the service life of the structure.

However, the design using total cost as a check index requires sophisticated knowledge and complex and advanced procedures. Here, a restorability check example9) using economy as a check index is introduced. In this method, the combination of fundamental period, yield seismic intensity and ductility factor of the structure which minimizes the total cost is calculated. The restorability is evaluated using the nomogram which is made based on the result of the calculation above.

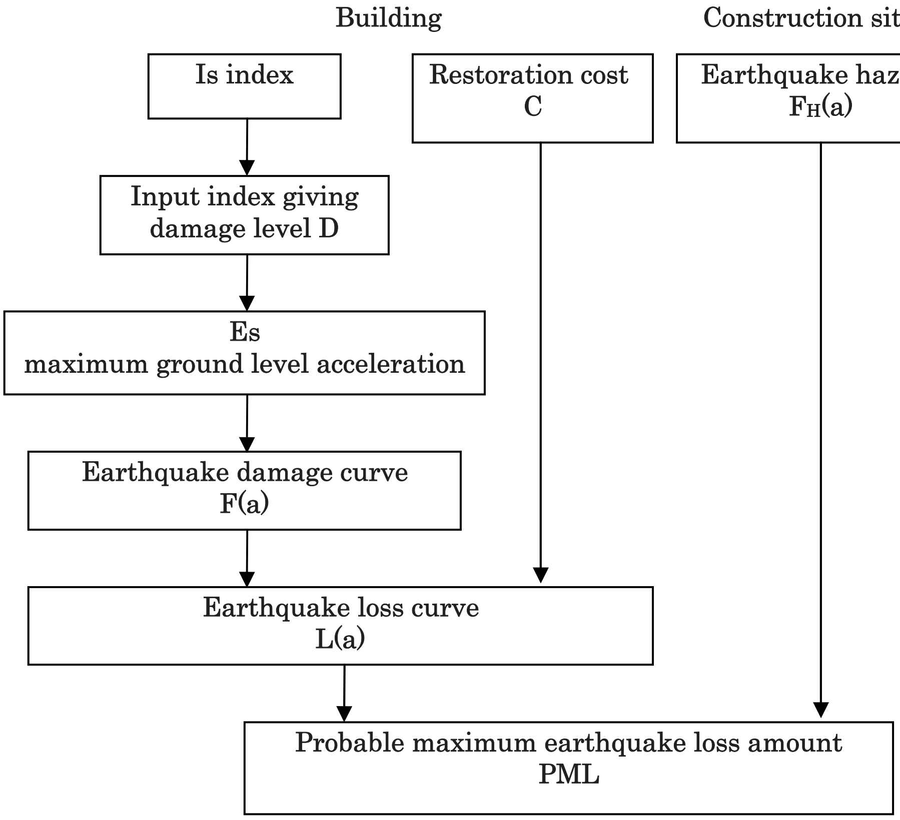
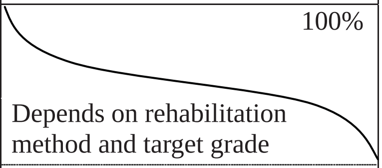


Fig. 4-1: Calculation Flow of Restoration Cost of Damaged Structure[2)]

Table 4-1: An Example of Seismic Performance Grade (Building Structures)

Earthquake Motion Level Seismic Performance	Level 1 Earthquake motion Rare earthquake motion Probability of exceedance 80% over 50 years (Seismic intensity V)	Level 2 Earthquake motion Very rare earthquake motion Probability of exceedance 10% over 50 years (Seismic intensity VI)
Seismic performance: High	(1) Function maintenance	(2) Limited function maintenance
Seismic performance: Medium	(2) Limited function maintenance	(2) Limited function maintenance (3) Structure maintenance
Seismic performance: Ordinary		(4) Not collapsed

Table 4-2: An Example of Seismic Performance State Matrix (Building Structures)

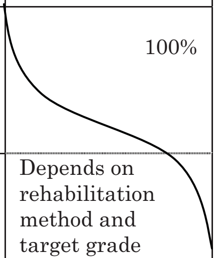
Assessment Item / State	Max. story drift angle (R)	Story ductility factor (μ)	Floor acceleration (cm/s^2)	Restoration Cost (Percentage of Initial Cost)
(1) Function maintenance	$R < 0.2\%$	$Q < Qc$ (no yielding)	< 300 (500)	0
(2) Limited function maintenance	$0.2 \leqq R < 0.5\%$	$\mu < \mu_u$	< 500 (1,000)	100% 
(3) Structure maintenance	$0.5\% \leqq R < 1.5\%$	$\mu < \mu_u /1.5(2.0)$	—	Depends on rehabilitation method and target grade
(4) Not collapsed	$1.5 \leqq R < 2.5\%$	$\mu < \mu_u$	—	Repair is rarely realistic
(5) Collapsed	$R > 2.5\%$	$\mu > \mu_u$	—	Rebuilding

Q_c: Story shear force at member yield; μ_u: Limit ductility factor of story
The values in parentheses can be set according to the target level, etc.

Table 4-3: An Example of Seismic Performance Grade (Bridges)

EQ motion Level / Seismic Performance		Level 1 Earthquake motion	Level 2 Earthquake motion	
			Roadway bridge	Railway Bridge
Seismic performance (High)		(1) Function maintenance	(2) Limited function maintenance	(2) Limited function maintenance (3) Structure maintenance
Seismic performance (Ordinary)	Seismic performance (Medium)	(1) Function maintenance	(3) Structure maintenance	(3) Structure maintenance (4) Structure just before collapse
	Seismic performance (Ordinary)			

Table 4-4: An Example State Matrix (Bridges)

Assessment Item / State	Displacement		Force		Restoration Cost (Percentage to Initial Cost)
	Roadway bridge	Railway bridge	Roadway bridge	Railway bridge	
(1) Function maintenance	—	$\theta <$ member disp. angle at yielding θ_y	Stress < Allowable stress	$M <$ yield moment M_y or $V <$ shear capacity V_y	0
(2) Limited function maintenance	Residual disp. < Allowable residual disp. δ_{Ra}	$\theta <$ max.disp. angle θ_u when significant loss of strength does not occur	Inertia force < lateral load carrying capacity Pa	—	100% 
(3) Structure maintenance	—	$\theta <$ max. disp. angle θn when yield strength is maintained	Inertia force < Lateral load carrying capacity Pa	—	Depends on rehabilitation method and target grade
(4) Just before collapsed	—	$\theta_n < \theta$	—	$M_y < M$ or $V_y < V$	Repair is not realistic
(5) Collapsed	—	—	—	—	Rebuilding

4.5 Summary

A framework of the performance-oriented seismic rehabilitation design was proposed in this chapter considering that the seismic rehabilitation performed for life cycle management, which aims at the continuous use of existing structures in the future, or performed as part of a business continuity plan, is one of the performance-oriented seismic rehabilitations. This framework consists of <1> the proposal of a performance matrix that consists of the combination of the assumed earthquake motion and the state of the structure, and <2> the method to set earthquake motion, to evaluate the structure state or to evaluate the earthquake motion that brings the structure to the state above. Furthermore, it consists of <3> checking the current state of restoration performance evaluation for repair cost estimation.

The continuous collection and review of the data of case studies regarding damage level and estimation of restoration cost, and construction interruption and economical loss is necessary to put the performance-oriented seismic rehabilitation design to practical use. Moreover, further research on methods to adequately evaluate the performance of existing structures that do not meet current regulations is also required.

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5. Application examples of performance-oriented seismic rehabilitation

5.1 Introduction

In this chapter, from various seismic rehabilitation projects that incorporated new seismic rehabilitation technologies, 12 application examples of building structures (government buildings, department stores, apartment buildings, schools, baseball stadium, etc.) and 10 application examples of civil engineering structures (roadway bridges, railway bridges, airport facilities, etc.), as a total of 22 examples were introduced classifying them into two categories, “seismic performance-oriented rehabilitation” and “constraint resolution type rehabilitation” (**Fig. 5-1**).

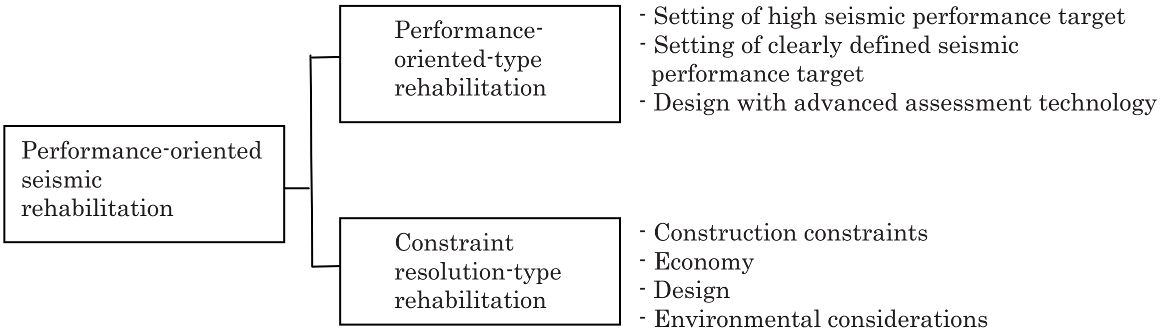

Fig. 5-1: Classification of Application Examples

5.2 Application examples of building structures

Since the use of buildings is very varied, the performance requirements of buildings are extremely wide ranging. Taking general buildings where people live as examples, the performances required for such buildings are listed in **Fig. 5-2**. Introducing application examples of building structures, the cases where the main objective was to improve seismic performance were categorized as "seismic performance-oriented rehabilitation application examples” (5 cases: **Table 5-1**), while the cases emphasizing the performances other than seismic performance, such as “habitability” and “productivity”, were categorized as "constraint resolution type rehabilitation application examples” (7 cases: **Table 5-2**).

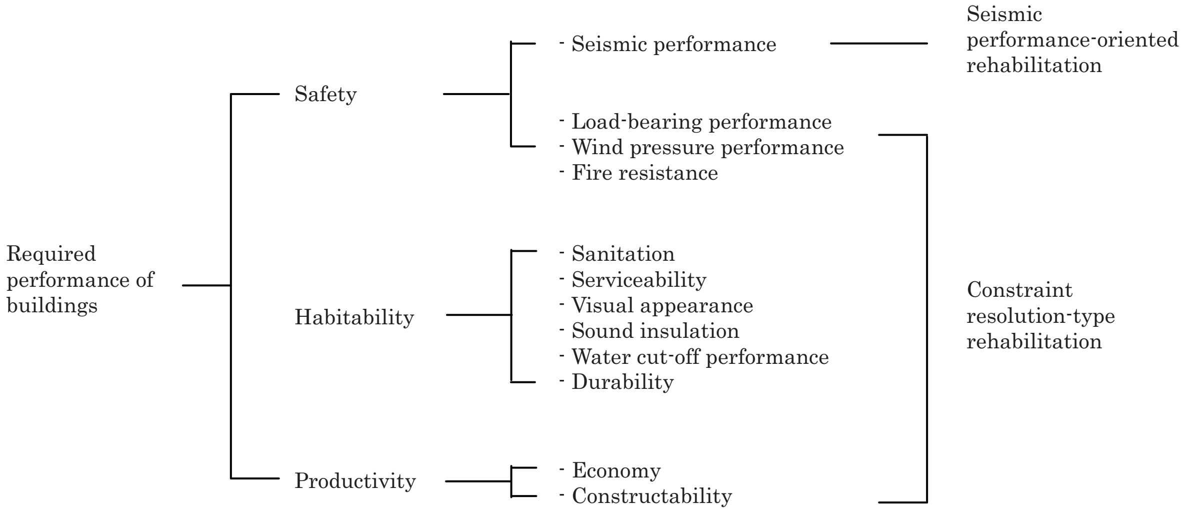

Fig. 5-2: Required Performance and Seismic Rehabilitation for Buildings

Table 5-1: Application Examples of Performance-oriented-Type Rehabilitation (Building Structures)

No.	Application Example	Structure Size	Rehabilitation Method	Seismic Performance
(1)	Government office building using mid-story isolation	SRC structure. 16 stories above ground and 2 stories basement	Mid-story seismic isolation using ground floor as isolation story	-Superstructure: level of short term allowable stress -Isolation story: displacement of 48 cm or less
(2)	Department store building using steel brace dampers	SRC structure. 8 above ground 2 stories basement	Seismic control rehabilitation using steel brace dampers	Inter-story displacement angle: 1/200 or less
(3)	Department store building using very low yield point steel braces	SRC structure 8 above ground 3 stories basement	Seismic control rehabilitation using very low yield point steel braces	Seismic index Is≥ 0.60; Ise ≥ 0.75 for rehabilitation
(4)	Apartment building exterior seismic control frames	SRC/RC structure 9 stories above ground	Seismic control using steel elasto-plastic dampers	Inter-story displacement angle: 1/100 or less
(5)	Apartment building using toggle seismic control braces	SRC/RC structure 11 stories above ground	Seismic control rehabilitation using toggle-type braces	Inter-story displacement angle: 1/125 or less

Table 5-2: Application Examples of Constraint Resolution-Type Rehabilitation (Building Structures)

No.	Application example	Structure Size	Rehabilitation Method	Constraints
(1)	Government building. Mid-story isolation to realize upper floor addition	SRC/S structure. 8 stories above ground	-Mid-story seismic isolation - Upper floors addition	- Construction using building - Superstructure upper extension
(2)	Apartment building on subway tunnel. Seismic isolation	SRC structure. 7 above ground 1 basement	Column top isolation	- Habitability and facade - Subway tunnel under the building
(3)	Apartment building. Exterior seismic control braces	RC structure. 5 stories above ground	Seismic control rehabilitation using exterior braces	- Construction using building - Reduction of noise and vibration
(4)	Government building. Seismic strengthening using exterior frames.	RC structure 5 above ground 1 basement	Strengthening using exterior frames	- Construction using building - Reduction of noise and vibration
(5)	Hanshin Koshien Baseball Stadium. Rehabilitation considering its 80-year history	RC structure with 3 stories above ground	Seismic strengthening using RC walls and exterior frames, etc.	- Phased rehabilitation - Measures to stop deterioration
(6)	Elementary school building. Seismic strengtnening considering its facade	RC structure with 4 stories above ground	Seismic strengthening using exterior braces.	- Short construction period - Safety of users during construction
(7)	University building. Integrated façade considering design and environment	RC structure. 5 above ground 1 basement	Seismic rehabilitation using buckling restrained braces	- Facade design - Reduction of energy load

5.3 Application examples of civil engineering structures

Following the 1995 Hyogoken Nanbu (Kobe) Earthquake, specifications and guidelines for the seismic design of newly built structures were revised, and the concepts and approaches of the design corresponding to these guidelines were applied also to the seismic rehabilitation of existing structures. The seismic rehabilitation in early stage was applied to piers in girder bridges which show relatively simple vibration modes. The technique to jacket existing piers with steel plates, reinforced concrete or fiber sheets, and so on was implemented. On the other hand, recent seismic rehabilitation is applied to the bridges with complex vibration modes such as cable-stayed bridges and truss bridges and so on. In the case of seismic rehabilitation of girder bridges and rigid frame viaducts, advanced rehabilitation techniques which are aiming, for example, at shorter construction periods, lower cost, reduction of noise and dust, no removal of bearing, which are adapted to severer work conditions, are used.

Based on the background above, ten seismic rehabilitation application examples of civil engineering structures since the year 2000 are introduced in this section sorting the examples into the "performance-oriented type seismic rehabilitation which particularly focused on the improvement of seismic performance (4 cases: **Table 5-3**) and the "constraint resolution type seismic rehabilitation examples (6 cases: **Table 5-4**) which particularly focused on the resolution of restraints in the construction for seismic rehabilitation.

Table 5-3: Application Examples of Performance-oriented-Type Seismic Rehabilitation (Civil Engineering Structures)

	Title	Structure	Rehabilitation Target	Rehabilitation Method	Characteristics
1	Rehabilitation of Hokuriku Expressway PC box girder bridge using seismic isolation	Roadway bridge	Bridge pier	- RC jacketing - Seismic isolation + carbon fiber jacketing	Damaged bridge by the 2007 Niigata Chuetsu-oki Earthquake
2	Reinforcement of viaduct piles associated with multistoried tracks of railway bridge	Railway bridge	Pile foundation	Foundation slab method	Existing piles are integrated with additional piles of lateral resistance only using foundation slabs
3	Rehabilitation of Seisho Bypass Bridge using concrete damper	Roadway bridge	Entire bridge	Concrete damper (ECC damper)	Improvement of energy absorption capacity of entire bridge by concrete dampers
4	Rehabilitation of Honshu-Shikoku Bridge Expressway bridge	Roadway bridge	-Entire bridge -Superstructure -Substructure -Displacement control structure	-Damping devices -Carbon fiber sheets -RC jacketing -Concrete blocks	Improvement of seismic performance of entire bridge and individual members. Bridge fall prevention structure is also reinforced.

Table 5-4: Application Examples of Constraint Resolution-Type Rehabilitation (Civil Engineering Structures)

Title		Structure	Target structure	Method	Constraints							
					(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	Roadway bridge located in median of main road	Roadway bridge	Bridge pier	Strut method	○	○					○	
2	RC rigid-frame viaduct columns of Sanyo Shinkansen	Railway bridge	Bridge pier	Jacketing using exterior spiral steel wire	○	○						
3	RC viaduct columns at rail station	Railway bridge	Bridge pier	Steel jacketing with interlock connections	○			○	○	○		
4	RC bridge pier of urban expressway integrated with building	Roadway bridge	Bridge pier	AC seismic rehabilitation method		○		○		○	○	
5	Railroad viaduct. Arch- type reinforcement considering design	Railway bridge	Viaduct	Arch support method	○							○
6	Rehabilitation of concrete structures in an airport.	Airport facility	Box culvert	Post-installed plate anchorage type shear reinforcing bars	○	○	○	○		○	○	

(1) Construction period, (2) Construction space, (3) Maintenance, (4) Light weighting, (5) Use of fire, water, (6) Reducing noise, vibration, (7) Removal (8) Design