Committee Report : JCI-TC046FS

Technical Committee on Assessment of Damage and Restorability of Reinforced Concrete Structures Damaged by Earthquakes

Nobuaki SHIRAI, Hikaru NAKAMURA, Hideyuki KINUGASA, Susumu KONO, Kaoru KOBAYASHI

Abstract

The objectives of the committee were to assess a degree of damage to be caused in reinforced concrete (hereafter refers to as RC) structures under severe earthquakes, to provide seismically safe and economical structures by means of appropriate repair and retrofit, and to establish such a seismic design method. For achieving these purposes, the committee collected and reviewed the previous works on the following items: (1) framework of the seismic design method toward better consideration of restorability, (2) current guidelines or standards relevant to the damage evaluation and control, and their applications to actually damaged structures, and (3) practical art-of-the-engineering related to the performance evaluation method of repaired and/or retrofitted structures.

Keywords: Restorability, Repair, Retrofit, Damage evaluation, Damage control, Economy, Mechanical capability

1. Introduction

Many concrete structures suffered severe damage during the Hyogo-ken Nanbu (Japan) Earthquake in 1995. As the lessons from this earthquake, a framework of the existing seismic design methods was reexamined. Consequently, a design framework is shifting toward performance-based seismic design and it introduces a concept of the ductility-based design as well, which explicitly takes dissipation of the energy absorbed after the yielding of structure into account in advance. In the performance-based seismic design, the required performances levels such as “Serviceability”, “Restorability (or Repairability)” and “Safety” shall be defined clearly in the first place. Then, the corresponding target level of the various limit states such as “Serviceability Limit State”, “Repairability Limit State” or “Safety Limit State” shall be established. Finally, it is necessary to ensure that responses of the structure against the expected excitation meet the target performance. In addition to the serviceability relevant to daily use, an interesting thing to note is that “Restorability ” for preserving the property against earthquakes is also included as a basic performance.

Under these circumstances, the technical committee on “Evaluation of Post-Retrofit Seismic Performance of RC Structures Damaged by Earthquake” was established as a theme of the feasibility study (FS) in the fiscal year of 2004. Several tasks to be dealt with in the future, including the need for understanding restorability of structures damaged by earthquakes, were extracted through the committee activities over one year[1]. The current committee, on the heels of the FS committee, aiming at establishing a “Framework of Restoration Performance-based Seismic Design Method,” has completed two-years of activities and the results are summarized here.

2. Committee Activities

It is noteworthy that a lot of research and committee activities regarding repair and/or retrofit of the damaged RC structures have been conducted for the past three decades. The characteristic of this committee among others is to aim at establishing a “Framework of Restoration Performance-based Seismic Design Method”. From the lessons obtained on the damage of RC structures which suffered from the past severe earthquakes; especially, the Hyogo-ken Nanbu (Japan) Earthquake in 1995 and Niigata-ken Chuetsu (Japan) Earthquake in 2004, the activities of the committee have mainly involved assessing a degree of damage to be caused in RC structures under severe earthquakes, providing seismically safe and economical structures by means of appropriate repair and retrofit, and establishing such seismic design methods. The committee members are listed in **Table 1**.

Table 1: Members of the Committee

Chairperson of Committee	Nobuaki SHIRAI	Nihon University
Assistant Chairperson of Committee	Hikaru NAKAMURA	Nagoya University
Chief of Subcommittee WG-1	Hideyuki KINUGASA	Tokyo University of Science
Chief of Subcommittee WG-2	Susumu KONO	Kyoto University
Chief of Subcommittee WG-3	Kaoru KOBAYASHI	East Japan Railway Company
Member	Atsushi ITO	Chubu University
	Hiroshi INAGUMA	Central Japan Railway Company
	Motoyuki OKANO	Obayashi Corporation
	Takashi KAWANO	Takenaka Corporation
	Kazuhiro KITAYAMA	Tokyo Metropolitan University
	Shigehiko SAITO	University of Yamanashi
	Junichi SAKAI	Public Works Research Institute
	Kazuo SUZUKI	Osaka University (Emeritus Professor)
	Eiichi SOU	Sho-Bond Corporation
	Kazushi TAKIMOTO	Shimizu Corporation
	Akira TASAI	Yokohama National University
	Kazuki TAJIMA	Nihon University
	Masaki MAEDA	Tohoku University
	Takeshi MAKI	Saitama University
	Tomohisa MUKAI	Building research Institute
	Hideo KATSUMATA	Obayashi Corporation
	Keiji KITAJIMA	Asunaro Aoki Construction Co., Ltd.
	Takashi FUJINAGA	Kobe University

In order to achieve the objectives stated above, the committee organized three subcommittees on the basis of a concept describing a variation in the performance of concrete structures accompanied by the deterioration with time, as shown in **Fig. 1**; that is, the subcommittee “WG-1” dealing with “Framework of Restoration Performance-based Seismic Design Method”, the subcommittee “WG-2” dealing with “Damage Evaluation”, and the subcommittee “WG-3” dealing with “Performance Evaluation Method of Retrofitted Structures”.

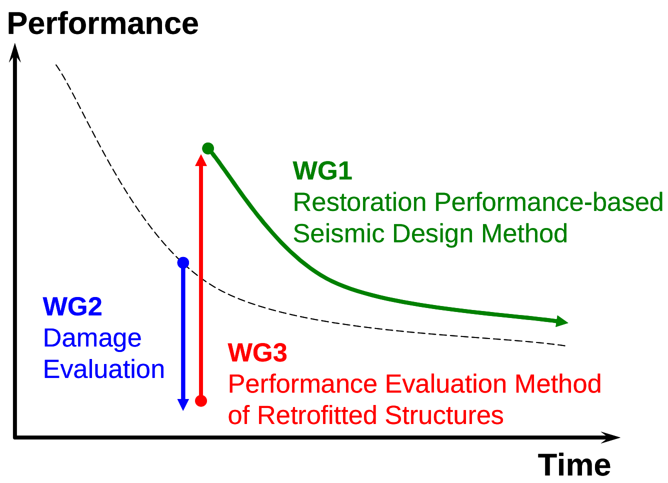

Figure 1: Placement of Different Subcommittees

The background as to why these subcommittees were organized is as follows. In the case that some structures suffered earthquake damage at a certain time and they are expected to be in service continuously by repairing and/or retrofitting, the following processes are thought to be important; that is, firstly evaluating the degree of performance deterioration caused in the structures in a quantitatively accurate manner (Damage Evaluation), then judging whether the retrofitted structures can be restored to their required performance level by applying appropriate repairing and/or retrofitting measures (Performance Evaluation Method of Retrofitted Structures), and finally checking whether the structures in question can be repaired or retrofitted in an economically reasonable manner when comparing the remaining service life and the cost required to restore their performance level (Evaluation of Restoration Performance). Furthermore, in the future it is required for structures to be engineered by taking these processes into account in advance during a design engineering stage.

3. Outline of Committee Report

The results obtained through the committee activities were compiled as a committee report with the content listed in **Table 2**. The following items are mainly included in the report:

(1) current guidelines or standards relevant to the damage evaluation and control, and their applications to actually damaged structures,

(2) important notices regarding the repair and retrofit methods, recent experimental examples, and performance verification of retrofitted test specimens by the analysis using the existing mechanical models, which are all needed to establish the performance

evaluation method for the retrofitted structures, and

(3) findings on the items and their background related to restorability, and proposals of the framework for the restoration performance-based seismic design method.

Table 2: Contents of Committee Report

1. Objectives of Committee
    1.1 Aims of committee
    1.2 Activities of committee
    1.3 Key Words
2. Discussion on Restorability of Actually Damaged Structures
    2.1 Civil engineering field
    2.2 Architectural engineering field
3. Damage Evaluation and Control
    3.1 Damage evaluation method in guidelines and standards
    3.2 State-of-the-art on damage evaluation and control
    3.3 Damage control
4. Performance Evaluation of Repaired Structures after Earthquake Damage
    4.1 Repair/retrofit of damaged structures
    4.2 Case studies on mechanical behaviors of damaged structures
    4.3 Mechanical performance evaluation after retrofit /repair
    4.4 Dynamic behaviors of repaired RC columns
    4.5 Remaining issues on performance evaluation of repaired/retrofitted structures
5. Seismic Design Method based on Restoration Performance
    5.1 Need of restoration performance-based seismic design method
    5.2 State-of-the-art on restorability in Japan and other countries
    5.3 Framework of restorability performance-based seismic design method
6. Conclusions

4. Damage Evaluation and Control

In Chapter **3**, the existing guidelines and standards related to the damage evaluation and control and their applications to actually damaged structures were reviewed, and the current state-of-the-art is described.

4.1 Damage evaluation method in guidelines and standards

In the field of architectural engineering, since it has been required to conduct a large number of seismic assessments for various new or existing buildings, the related organizations such as AIJ (Architectural Institute of Japan) and JBDPA (Japan Building Disaster Prevention Association) have developed guidelines and/or standards in a user-friendly format. In this report, “Standard for Seismic Evaluation of Existing RC Buildings (JBDPA)”, “Guidelines for

Post-earthquake Damage Evaluation and Rehabilitation (JBDPA)", "Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings (AIJ)" and "FEMA356-Prestandard and Commentary for the Seismic Rehabilitation of Buildings (ASCE: American Society of Civil Engineers)", which have been often utilized in the field of the architectural engineering, are reviewed. In the "Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings (AIJ)", for example, it is required to confirm that an index defining the seismic performance of a newly designed building exceeds the standard level as usual. In addition, an important point to note is that the potential seismic performance level is quantified in terms of either deterministic or probability value. This guideline defines three levels corresponding to "serviceability", "repairability" and "safety" as the limit states and calculates the probabilities of a building exceeding the respective limit states under ground motions that are expected to occur during its service life. The characteristic of this guideline is that the performance at various limit states is evaluated mainly based on the flexural and shear deformation as shown in **Fig.2**. Finally, the index indicating the potential seismic performance of a building is defined as the ratio of the reference seismic intensity to the limit seismic intensity.

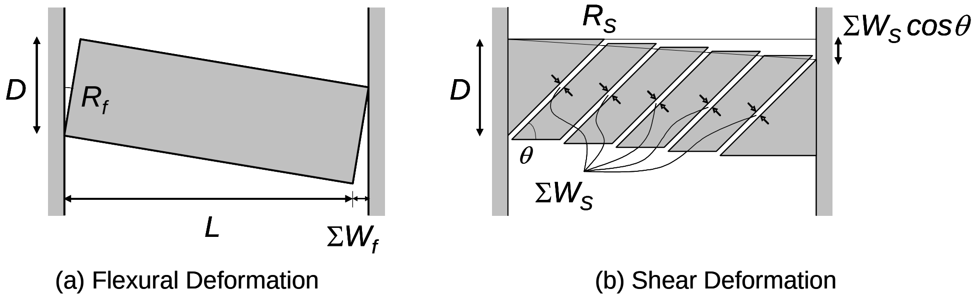

Figure 2: Deformation Model of Beam Component Used for Damage Evaluation [2]

In the field of civil engineering, on the other hand, since seismic performance level of structures damaged by earthquakes has to be evaluated by taking the social and economical elements during a disaster into account, degree of damage and rehabilitation measures have to be evaluated or determined for each case and thus guidelines and standards are not developed as those in architectural engineering. Ideally, it is expected that the civil structures would not suffer damage even under severe earthquakes. However, even if the existing civil structures have been seismically retrofitted, it is easily imagined that they may suffer damage due to a variety of seismic intensities to be expected. The following measures or procedures are needed to restore the damaged civil structures in early stages:

(1) The seismic performance of the concerned structure has been evaluated in advance and the expected damage part(s) in the structure have been predicted;

(2) The required seismic retrofit has been executed to reduce the degree of expected damage;

(3) The appropriate damage evaluation method has been established to judge quickly whether repair or retrofit of the damaged structure is needed or not, or whether a sustainable service is possible or not; and

(4) The repair and/or retrofit method or replacement method corresponding to a degree of damage has been prepared.

In this report, the current states and issues of (1) to (3) among the measures listed above, which are important to restore damaged concrete structures such as railroads and highway bridges, are explained in detail (see **Fig.3**).

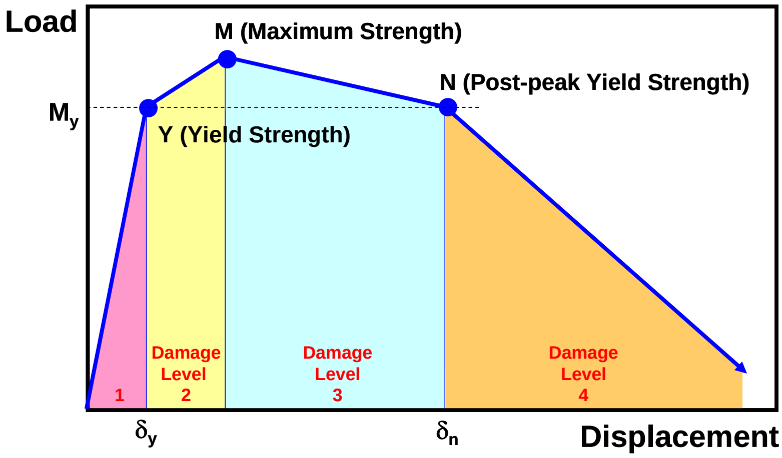

Figure 3: Relationship between Load-Displacement Curve and Damage Level : Example in Railroad Structures

4.2 State-of-the-art of damage evaluation and control

With reference to the determination method of various limit states provided by the "Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings (AIJ)", the relationship between the limit states and the damage evaluation is reviewed. Furthermore, as an example of the challenges in the United States, a methodology for determining the safety limit state or the overall failure state of structures is introduced as well as the next-generation performance-based seismic assessment procedures proposed by PEER (Pacific Earthquake Engineering Research).

The recent case studies for predicting the residual seismic capacity of damaged structures includes the evaluation of the relationship between residual crack width and deformation of the structural component, the relationship between residual crack width and residual seismic capacity of the structural component, the residual seismic capacity of a column by pseudo-dynamic testing, and the residual seismic capacity of a structure by earthquake response analysis. Furthermore, the evaluation of seismic capacity of a building strengthened by the conventional method, the case of actual damage in a retrofitted building, dynamic behavior of a framed structure having isolators or seismic control devices during ground motion are introduced.

If the damage level of a structure due to an earthquake is predictable, “damage control” such as how to reduce, suppress or control its damage level becomes an important task as a next step. However, technologies related to damage control are diverse and include; for example, (1) damage control of the overall structure by means of base isolation or seismic control (see **Fig. 4**), (2) damage control of structural components by means of utilization of pre-stressed concrete or un-bonded reinforcing bars, and (3) damage control by a newly developed material technology with fiber reinforced concrete. Thus, the state-of-the-art of research and development in the field of damage control is reviewed in this section.

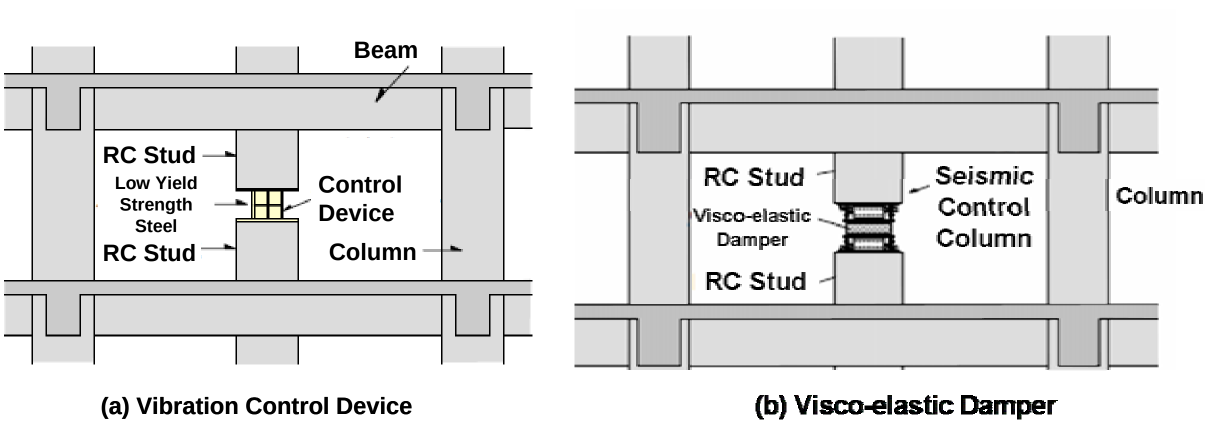

Figure 4: Reinforced Framed Structure Installed with Seismic Control Devices [3,4]

5. Performance Evaluation of Repaired Structures after Earthquake Damage

This chapter introduces the recent research activities on the development of methods for the seismic performance evaluation of retroffited and/or repaired structures that undergo damage during extreme earthquakes. Recent experimental and analytical approaches are reviewed and summarized.

5.1 Case studies on seismic performance of repaired structures

5.1.1 Previous studies on stiffness evaluation of repaired structures

Studies on stiffness evaluation of repaired structures over the past 20 years were reviewed, with the main findings summarized as follows:

(a) The initial stiffness after retrofitting and/or repair decreases compared with that at a non-damaged state. This is because it is not possible to grout resin into all cracks and because the elastic modulus of the material used for repair is smaller than that of concrete.

(b) It is difficult to restore the original performance simply by replacement of cover concrete.

(c) The flexural strength of repaired structures is larger than that of non-damaged structures. This may be due to the strain hardening and aging effect of reinforcing bars and the contribution of the tensile strength of materials used for repair.

5.1.2 Experimental applications to building structures

Recent experimental studies of building structures are reviewed in this subsection; namely:

(1) the shaking table test on a repaired and retrofitted 4-story framed RC structure [5]; and

(2) the experimental studies on steel and concrete composite framed structures[6].

A 1/4-scaled 4-story framed structure was tested on a shaking table subjected to three-dimensional earthquake excitation. The test specimen before undergoing damage is shown in **Photo 1**. The results indicate that the repair and retrofit methods were effective in recovering the seismic performance of damaged structures, and it was verified that post-repair and/or retrofit behaviors can be estimated on the results obtained from the component tests.

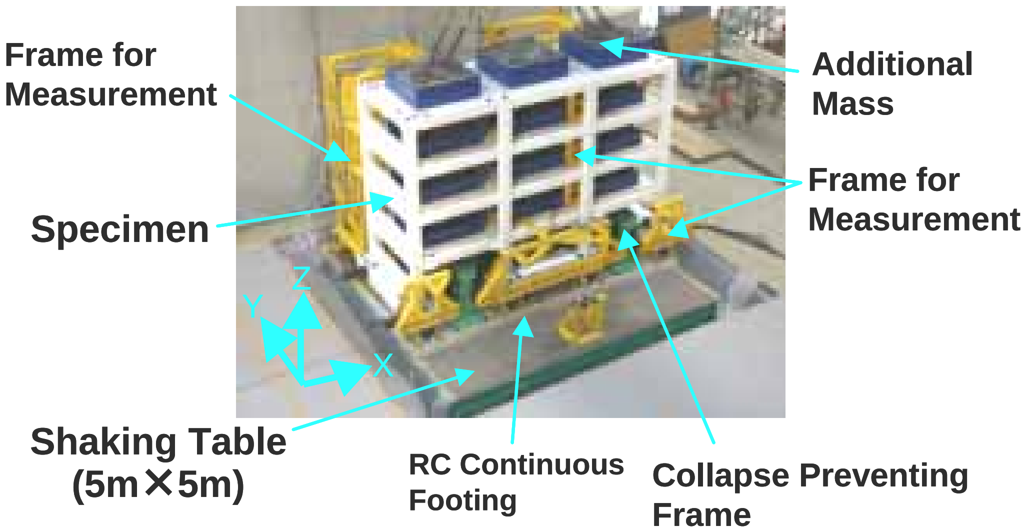

Photo 1: Framed Structure Specimen on Shaking Table (Before Damage)

5.1.3 Experimental applications to bridge structures

Among the recent experimental case studies on bridge structures, a series of cyclic tests on bridge columns of railroad structures [8,9,10] were reviewed. A verification test on column components was conducted to investigate the effect of repairing methods depending on the degree of damage [8]. It was more effective to recover the initial stiffness and the flexural capacity when specimens with higher degrees of damage were repaired. On the other hand, the effectiveness of repairing methods on ductility capacity was relatively worse for those with higher degrees of damage

5.2 Evaluation of seismic performance after retrofit or repair

To provide basic information for the development of methods of evaluating the seismic performance of repaired specimens, a series of analyses on repaired structures were conducted using the fiber model and the component-basis mechanical model. The main findings are summarized below.

5.2.1 Analyses of repaired RC columns using fiber model

A series of analyses was conducted by using the fiber model for a RC column specimen of a railroad column structure to investigate the applicability of the analytical model to structures repaired after earthquake damage. The specimen was first tested under quasi-static cyclic loading to simulate earthquake damage, the damaged portion around the bottom of the column were repaired by using epoxy resin grout, and then the repaired specimen was again tested under quasi-static cyclic loading. The effect of the mechanical properties of epoxy resin, which was used to repair the damaged concrete section, and the longitudinal reinforcement was investigated. The lateral force versus lateral displacement hysteresis of the repaired specimen obtained from the analysis is shown in **Fig. 5**.

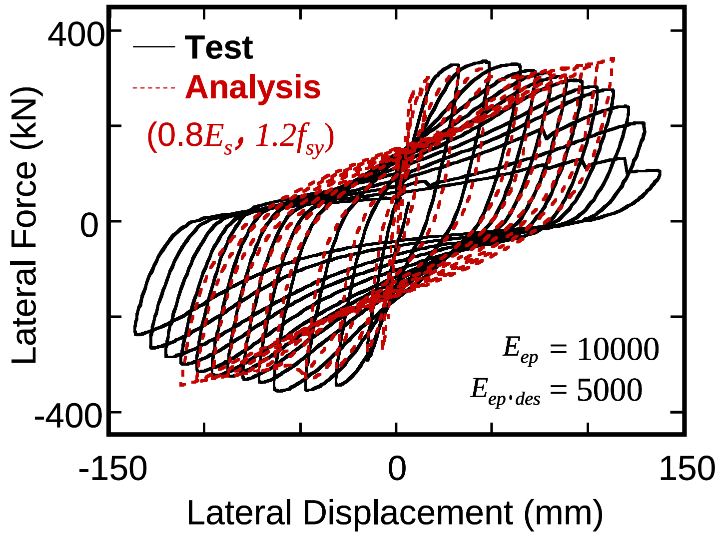

Figure 5: Typical Simulation Result by Fiber Model

Although the analysis was conducted under simplified conditions, the skeleton curve obtained from the analysis (shown in **Fig. 5**) shows good agreement with that from the test. The analysis was able to simulate a reduction in the initial flexural stiffness observed in the retrofitted condition by reducing the initial modulus of longitudinal bars by 20 percent. In addition, the accuracy of the analysis was improved by increasing the yielding strength of the longitudinal bars by 20 percent in order to take into account the strain hardening effect of the longitudinal bars.

5.2.2 Analyses of post-retrofit SRC components by fiber model

Behaviors of SRC (Steel Reinforced Concrete) columns and framed structures that were retrofitted by carbon fiber sheets were simulated by using the two-component model, composed of the fiber model used for the plastic hinge region and the elastic body. The confinement effect of carbon fiber sheets was taken into account by using the modified stress versus strain relationship of concrete.

The analysis shows good agreement with the observed behaviors, if the equivalent length of plastic hinge is assumed to 2.5*D* so that the calculated initial stiffness matches that of the test; where *D* is the depth of the cross section.

5.2.3 Analyses of repaired RC beams by FEM

Figure 6 shows the model RC beam specimen designed to fail in shear and the corresponding analytical model (mesh division) for FEM analysis. **Figure 7** shows the calculated load versus displacement relationships for the beam specimen before damage and after the repair. The repair was done by grouting resin into cracks.

The analysis is executed as follows. Unloading is done after the model RC beam specimen has failed in shear by the initial loading analysis, and information regarding damage caused in the beam is obtained. In the analysis for repaired status, first the damage information obtained in the previous step is transferred to the analytical model for the repaired one and the repairing effect is modeled, and then the loading analysis is again conducted in the same way as the initial loading analysis. The effect of grouting into cracks is modeled as a macroscopic variation in the stiffness of the cracked concrete, which was repaired according to a size of the residual crack widths, and recovery in the tensile strength of cracked concrete. The analysis shows a good agreement with the results obtained from the previous test observations [11, 12].

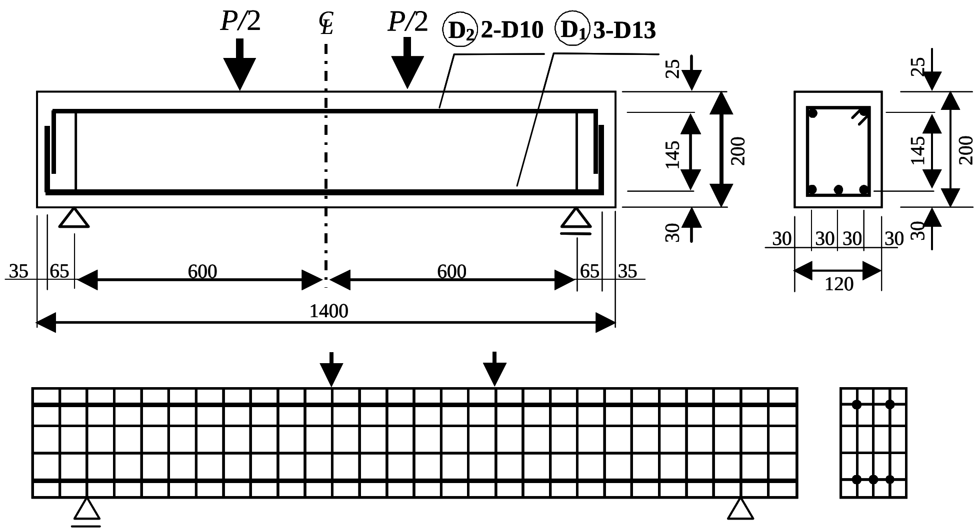

Figure 6: Configuration and Detail of Model Beam Specimen and Mesh Division

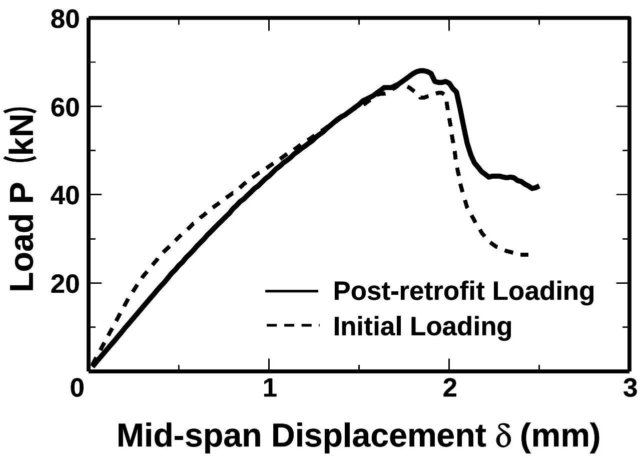

Figure 7: Measured and Predicted Load – Displacement Relationship

5.3 Dynamic behaviors of repaired RC columns

5.3.1 Analyses of dynamic behaviors of repaired RC columns by fiber model

In order to evaluate dynamic behaviors of the repaired RC columns, earthquake response analyses were conducted using the same model as that stated in the subsection **5.2.1**. According to the results, the maximum response displacement for the repaired column may increase by 27 percent. Because the dynamic response of a non-damaged structure and repaired structure depends on the dynamic response properties of the structure and the dominant period of ground motions, further investigations are necessary for variations of structures and ground motions.

5.3.2 Analyses of dynamic behaviors of retrofitted 5-story RC building structure

In order to understand dynamic behaviors of a retrofitted 5-story RC building structure subjected to a strong ground motion, the dynamic response analyses were conducted with an analysis model developed by taking into account the reduction in the component stiffness and incremental increases in the component strength by retrofitting.

In the case that the response exceeds the point on the skeleton curve defined by the maximum strength and the prescribed drift angle, remarkable differences in the models for the non-damaged structure and the retrofitted structure are observed. Assuming that the structure was damaged uniformly along the total height, the lateral stiffness at all stories was reduced in the analytical model. However, it seems in the actual situation that the magnitude of the stiffness reduction varies depending on the degree of damage. Furthermore, the contribution of the slabs and non-structural components to the stiffness should be included. Further research is needed to refine an analytical modeling of the skeleton curve.

6. Seismic Design Method based on Restoration Performance

In general, the seismic design has been conducted so far under a primary target of protecting lives against strong earthquakes. It is hard to say that the design practice has been executed by establishing design targets or damage limits explicitly for reducing economic losses. In order to reduce expected economic losses to be caused by coming severe earthquakes, it is necessary to establish a seismic design method which aims at securing the restorability of civil and building structures supporting economic activities.

6.1 State-of-the-art on restorability in Japan and other countries

After the Loma Prieta earthquake in 1989 and the Northridge earthquake in 1994 in the United States, Vision2000 and FEMA356 (Federal Emergency Management Agency) were drawn up. These documents, which are the first generation guidelines for performance-based seismic design, aim at not only safeguarding life but also maintaining functionality, taking into account the enormous economic losses that big cities located along the west coast suffered during these earthquakes. ACT (Applied Technology Council) and PEER (Pacific Earthquake Engineering Research Center) are actively developing next generation guidelines for performance-based seismic design at present. In those guidelines, “downtime” and “repair costs” due to earthquakes are defined as an important index for evaluating the seismic performance of buildings.

On the other hand, people in the economic world take a great interest in concepts referred to as “PML” or “BCP”. PML (Probable Maximum Loss) is an index for evaluating an asset value of real estate against a seismic risk. PML originally an index used for insurance against fire, has also been used for risk evaluation against damage caused by a large earthquake. In Japan, PML has been utilized as an index for determining a limit amount of total payment since the foundation in 1967 of the insurance system and has become an important index for its operation. In recent years, PML has been used in the building and real estate industries, in which the definition of PML is that the annual exceedance probability of seismic loss is equal to 1/475.

The BCP (Business Continuity Plan) has rapidly attracted a great deal of attention in Japan since the Niigata-ken Chuetsu (Japan) Earthquake in 2004 that forced the shutdown of a certain electric company and caused a huge amount of economic loss on account of the ripple effect thereof. Since BCP aims to reduce the downtime of economic activities after earthquakes and to minimize the economic loss as small as possible, it is composed of a supposition of disasters, evaluation of their impacts and losses, supposition of affected damage in key businesses and extraction of important elements among elements interrupting business.

The “downtime” and the “repair costs” due to earthquakes are important information for decision-makers who need a performance description that relates more directly to economic loss. There is a tendency in the world to develop a rational design method including the “downtime” and the “repair costs” as one of the seismic performance indices for structures.

6.2 Framework of restorability performance-based seismic design method

It is required to follow the following procedure for achieving restoration performance-based seismic design after earthquake disasters (see **Fig. 8**):

Step 1: Analyze characteristics of the building from the viewpoint of restorability;

Step 2: Determine appropriate target criteria for the restoration performance; and

Step 3: Design structures or check their performance on the basis of the criteria in Step 2.

The committee investigated steps 1 and 2 among three steps. The framework of the seismic design method presented in this report is based on the following three basic items:

(1) Restoration performance is defined as the performance to be able to be restored in an economically reasonable manner.

(2) Restoration performance shall be evaluated on the basis of cost and time needed to restore.

(3) Restoration performance shall be used as performance independent of the safety performance.

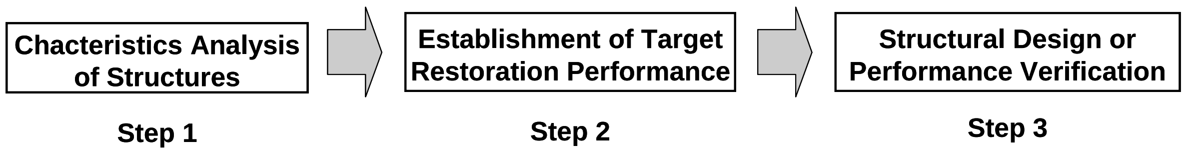

Figure 8: Design Procedure

6.3 Establishment of target restoration performance (Step 2 in Fig. 8)

From the viewpoint of the economy, it is necessary to judge effectiveness of the restoration by taking not only the recovered mechanical capacity of structures but also the cost and the time required for restoration into account. Some cases consider only one of them; that is, either cost or time, depending on the type of structure in question, but both must be considered in many cases. Thus, it is suggested to represent the target restoration performance in three-dimensional space in terms of the ground motion intensity, the repair cost and the restoration time as shown in **Fig. 9**.

The expected ground motion has three levels; that is, (1) frequent small and moderate earthquake (B) having a probability of exceedance of 50% in 50 years, (2) severe earthquake (A) having a probability of exceedance of 10% in 50 years, and (3) an extremely severe earthquake having a probability of exceedance of 2% in 50 years. Also, the restorability shall be expressed by four levels; that is, (1) hardly any problem, (2) somehow safe, (3) permissible at the least and (4) not permissible. Now, let the boundary values of the restoration time be set at 3 days, 3 weeks and 3 months and also let the boundary values of the repair cost ratio, that is, a ratio of the repair cost to the initial construction cost, be set at 5, 15 and 30 percent. The "basic diagram" is illustrated in **Fig. 10**.

The validity of these values is studied sufficiently in “Step 1; Analysis of characteristics of structures” shown in **Fig. 8** and will be explained in the next section.

Since it seems that the restoration performance has a tradeoff relation to the safety performance, it is needed to examine how the restoration performance obtained is correlated with the safety performance. For this purpose, three-dimensional representation in terms of the ground motion intensity, the repair cost and the restoration performance becomes important.

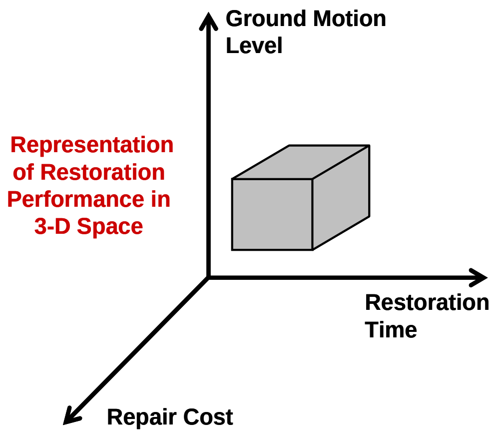

Figure 9: Representation of Restoration Performance in 3-D Space

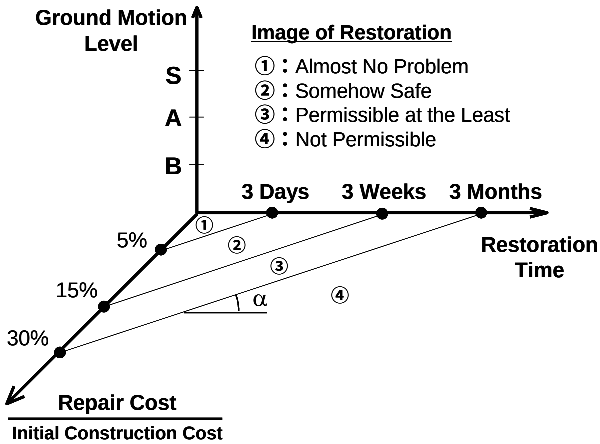

Figure 10: Representation of Restoration (Basic Diagram)

6.4 Analysis of characteristics of structures from viewpoint of restoration performance (Step 1 in Fig. 8)

It is required that characteristics of the structure be analyzed from the viewpoint of the restoration performance and the structure be designed in an optimum engineering manner. If characteristics regarding the restoration performance could be analyzed in detail, it will be possible to execute a seismic design in consideration of the restoration performance with high reliability. The analysis of characteristics shall be conducted for the following four items:

(1) Which causes more economic loss; repair cost or restoration time?

(2) What are the admissible levels of repair cost and restoration time? (That is, is the boundary of 3 days, 3 weeks and 3 months for the restoration time adequate, and the boundary of 5, 15 and 30 percent for the repair cost ratio adequate?)

(3) Which is dominant in the damaged structure; repair cost or restoration time?

(4) Are safety and restorability well-balanced? (Is the tradeoff between safety and restorability reasonable?)

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