Proposal of repair index and strategy for recovery of reinforced concrete buildings damaged by earthquakes

M. Maeda, T. Nagai & R. Akiya
Tohoku University, Sendai, Japan.

K. Miura
Obayashi Corporation/The University of Auckland, Tokyo/Auckland, Japan/New Zealand.

A.V. Shegay
The University of Auckland, Auckland, New Zealand.

M. Seki
Building Research Institute, Tsukuba, Japan.

ABSTRACT

Restoration of damaged buildings is an important issue for achieving smooth recovery of society after a devasting earthquake disaster. In general, in past earthquake disasters in Japan, demolition or repair judgement was made based on damage level of the target building using the “Japanese Damage Level Classification Standard (2015)”. However, as cost effectiveness is not considered in the judgement, all the damaged parts of the structure are generally repaired. In this regard, a reasonable evaluation methodology and judging criteria is necessary for strategic decision making of repair and recovery of damaged buildings.

This research develops and proposes a “Repair Index” to estimate the effectiveness of different repair schemes for damaged reinforced concrete (RC) buildings for selection of most reasonable scheme. The basic concept of the “Repair Index”, which consist of (1) structural capacity recovery, (2) repair cost and (3) economic loss indices, is introduced.

Firstly, recovery ratio of structural capacity was investigated based on previous research and experiments, and a database was developed. Secondly, an evaluation method of repair cost and economic loss considering expected cost and loss in future earthquakes was proposed. and applied to a prototype RC building. Finally, Repair Index was applied to a prototype RC building and the most reasonable and cost-effective repair strategy was discussed.

1 INTRODUCTION

Restoration of damaged buildings is important to achieve rapid recovery of society after devasting earthquake disasters. In general, in past earthquake disasters in Japan, judgement of demolition or repair was made based on the damage level of the target building using "Guidelines for Post-earthquake Damage Evaluation and Rehabilitation of RC Buildings", JBDPA (2015). However, cost effectiveness of recovery against future earthquakes has not been considered in the judgement, leading to repair of all damaged structural elements. In this regard, a reasonable evaluation methodology and judging criteria is necessary for reasonable decision making of repair and recovery of damaged buildings. Kinugasa et al. (2019) proposed an index to evaluate the severity of earthquake damage from the viewpoint of post-seismic functional recovery. It was based on repair time and the objective is to compare the functional recovery in different structural designs assuming that all damaged members are repaired. Regarding repair cost, Polese et al. (2015) developed a method to estimate repair cost based on relationships between seismic performance deterioration and repair cost calibrated by the data of damaged buildings after 2009 L'Aquila earthquake. However, both methods don't consider indirect economic loss caused by suspension of business suspension, etc. and cannot investigate multiple repair strategies of a building to identify the most reasonable plan.

The final goal of this research is to develop a "Repair Index" to evaluate the effectiveness of different repair strategies for damaged reinforced concrete buildings quantitatively and enable decision makers (building owners) to choose the most reasonable repair and/or recovery solution. The basic concept of the proposed "Repair Index" is shown in Figure 1. The index considers (1) structural performance recovery, (2) repair cost and (3) economic loss, was introduced first. Then, an evaluation method of structural performance recovery was developed based on previous test results of structural components and a structure. Also, a method to evaluate repair cost and economic loss was shown. Finally, Repair Index was calculated for the prototype 5-story frame structure and the effectiveness of the proposed method was verified.

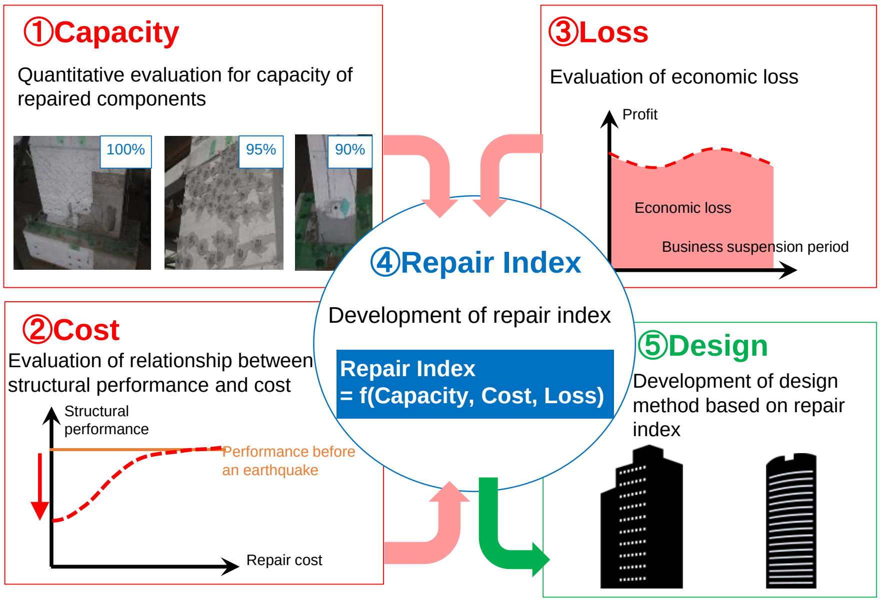


Figure 1: Overview of the research

2 BASIC CONCEPT OF REPAIR INDEX

2.1 Target of research

After a damaging earthquake, buildings which escaped from damage can be used without repair work and buildings which collapsed or suffered significant damage need to be demolished. However, in most cases, the damage state of a building is between these two clear conditions as shown in Figure 2. In such cases, it is difficult for these moderately damaged buildings to devise reasonable decision. It's because there is no established framework and judging criteria for evaluating repairability.

The objective of this research is to develop a "Repair Index" to assist relevant stakeholders (building owners, insurance, local authorities, designers etc.) in recovery of the damaged buildings such that the most reasonable recovery decision can be achieved.

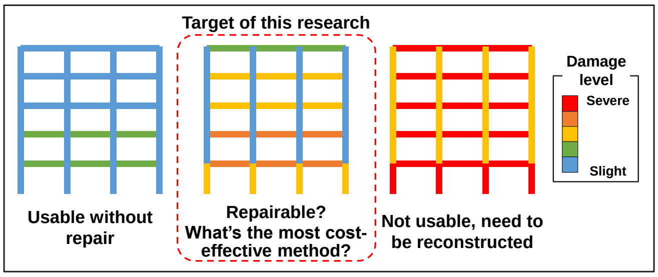


Figure 2: Different damage states of buildings and the target of this research

2.2 Introduction of limited repair concept

As a repair strategy, limited repair concept was introduced in this study. In general, all the damaged parts (cracked and crushed concrete, buckled and fractured reinforcing bars) in a building are fully repaired (called "full repair", hereafter). The main reason may be that the performance of buildings can become uncertain in case some components (e.g., beams on the upper floor) and/or some parts of the components (e.g., mid-height of columns) are not repaired. Although "full repair" is the best option to recover the original structural performance, it might not necessarily be the most cost and time efficient than the required to achieve compliant performance. Therefore, in this research, two new concepts of "limited repair" are proposed. These concepts are shown in Figure 3. The first is a component level limited repair named "partial repair" in which only parts of damaged member are repaired. The second is a system level limited repair named "selective repair" in which only some of damaged members are repaired or partially repaired. The options of limited repaired can be taken in repair scheme only if the resulting performance is evaluated and assured.

2.3 Introduction of Repair Index

The basic idea to calculate the Repair Index (RI) is shown in Figure 4. RI is calculated for a building damaged by an earthquake as a ratio of the total required costs incurred when the building is repaired (full repair, selective repair etc.) to total required costs when it is rebuilt. Total required costs is defined as the summation of the repair cost, economic loss due to suspension of use of the building, and expected repair/economic loss costs incurred in future earthquakes as a result of the chosen repair strategy. An advantage of this method is that it includes expected cost which is not considered in most of previous studies and enable an evaluation based on total cost over the entire lifecycle.

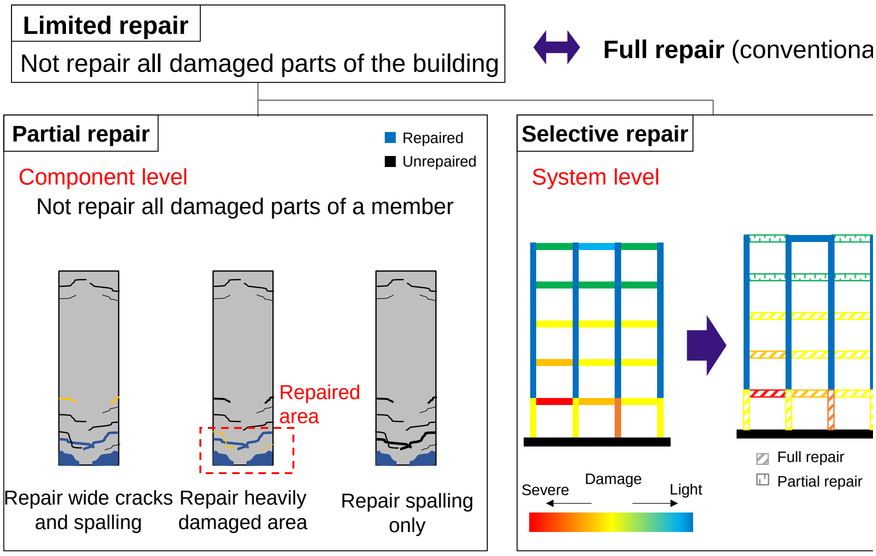


Figure 3: Basic idea of "Partial repair" and "Selective repair"

The Repair Index can evaluate two things. The first is to compare whether reconstruction or repair is more efficient. If the RI value is lower than 1, it means that the candidate repair method is more reasonable than reconstruction in terms of cost effectiveness because it reduces the total required cost during the service period of the building. On the other hand, in case of RI value larger than 1, reconstruction is more reasonable. The second is to compare which repair plan is the most efficient. As the total required costs during repair depends on a repair method, RI can be defined for each repair method. So, comparing RI indices of possible repair methods, the lowest RI value can indicate the most reasonable repair method.

$$RI = \frac{Total\ required\ cost_{\ Repair}}{Total\ required\ cost_{\ Reconstruction}} \quad \begin{cases} < 1 \cdots \textbf{Repair} \text{ is more efficient} \\ > 1 \cdots \textbf{Reconstruction} \text{ is more efficient} \end{cases}$$

$*\ Total\ required\ cost = Repair(Rebuild)\ Cost + Economic\ Loss\ (include\ expected\ values)$

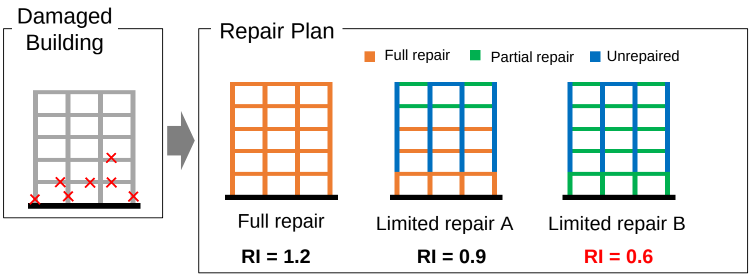


Figure 4: Fundamental formula and examples of application of Repair Index

3 PERFORMANCE RECOVERY OF SEISMIC CAPACITY OF REPAIRED STRUCTURE

3.1 Recovery of capacity of structural elements

In the calculation of Repair Index, RI, it is necessary to evaluate seismic capacity recovery of a repaired structure to estimate expected response due to future earthquakes. In this research, the capacity-spectrum-method-based approach was employed to evaluate relationships between seismic performance and total required cost in repaired buildings. Figure 5 shows concept of Seismic Capacity Index α in the Japanese "Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings", (AIJ, 2004). The Seismic Capacity Index α is defined as the ratio of intensity of response as the building's safety limit state to the design standard ground motion. This may be an indicator of the building's overall seismic performance. Performance curves can be derived from push-over analysis of a target building structure. Figure 6 shows (a) frame model and (b) analytical model of structural element. Backbones of repaired components were modelled, as shown in Figure 6 (c) by multiplying recovery factors (described in 3.2 in detail) of initial stiffness (Φsi), yielding stiffness (Φsy) and strength (Φq) to backbones of undamaged components. Cyclic behaviour of each spring is modelled using the Takeda model, and the hysteresis loop area is reduced based on recovery factors of damping (Φh).

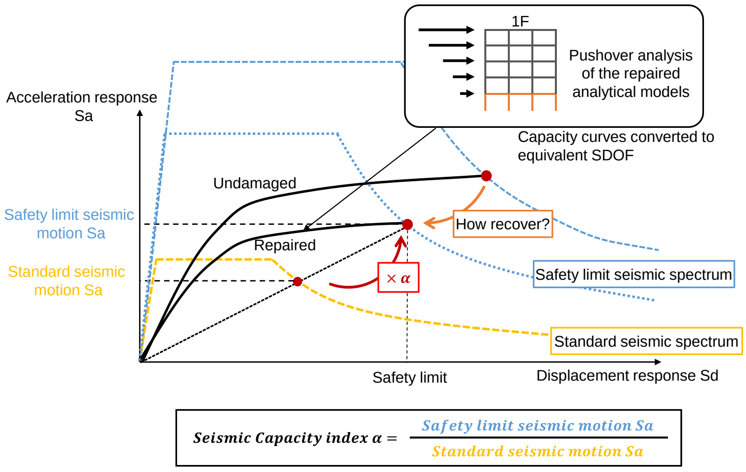
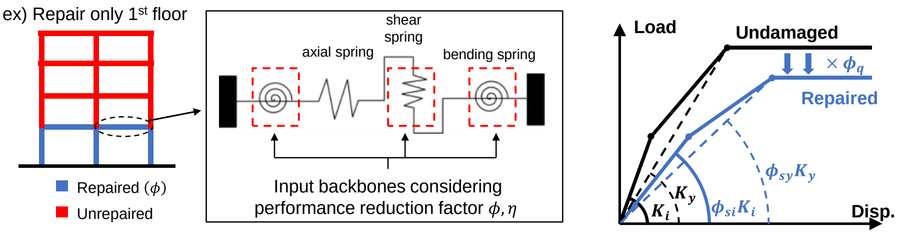


Figure 5: Conceptual diagram of seismic capacity index



(a) Frame analytical model (b) Liner element model (c) Backbone curve model

Figure 6: Modeling method of repaired frames

3.2 Recovery of capacity of structural elements

Regarding performance recovery factors, the performance recovery factors Φ for strength, yielding secant stiffness and deformation capacity are provided in FEMA 306 (1998) for RC walls and coupling beams. However, the target building type for FEMA 306 is limited to wall type buildings; therefore, performance recovery factors for moment-frame components such as beams and columns are not included. In addition, recovery factors for damping (energy dissipation capacity) are not considered. A database of recovery factors Φ were developed based on previous experimental results and static loading tests of RC elements were conducted to obtain data by Miura et al. (2023).

3.2.1 Database for capacity recovery factor

A database of structural capacity recovery factor Φ was developed by Mikawa et al. (2022) as shown in Table 1. The database includes repair RC columns, beams and walls with different failure modes (shear or flexural) and damage levels according to Japanese "Post-EQ Damage Evaluation Guideline", (JBDPA, 2015).

The most popular repair technique for damaged RC elements in Japanese practice is epoxy injection to cracks as shown in Figure 7 (a) in case of damage level I (slight damage) and II (minor damage). For higher damage levels, mortar patching to spalled and/or crushed concrete, as shown in Figure 7 (b) is applied in addition to epoxy injection.

Table 1: Database of structural capacity recovery factors for RC components (Mikawa et al. 2022).

ϕ_{si}:initial stiffness ϕ_{sy}:Yielding stiffness ϕ_q:Strength

		Damage level														
		I			II			III			IV			V		
Component type	Failure mechanism	ϕ_{si}	ϕ_{sy}	ϕ_q	ϕ_{si}	ϕ_{sy}	ϕ_q	ϕ_{si}	ϕ_{sy}	ϕ_q	ϕ_{si}	ϕ_{sy}	ϕ_q	ϕ_{si}	ϕ_{sy}	ϕ_q
Beam	Shear															
	Flexural				1.58	1.08	1.16				0.63	0.70	0.93			
Column	Shear															
	Flexural				0.79	0.86	1.04	0.77	0.78	1.08				0.29	0.53	1.12
Wall	Shear										0.45	0.77	0.82			
	Flexural				0.54	0.84	1.03				0.55	0.75	1.09			

Areas with insufficient data

3.2.2 Experiment for capacity recovery factor

To fill the database, we need to know the performance of the component before and after repair by experimentation. Here is a brief introduction of the experiments we conducted. Static loading tests of RC beams and wall specimens with different damage levels (moderate and severe) were carried out to investigate effect of conventional repair techniques, Miura K. et al (2023). This experiment was performed with a parameter of the degree of damage. Specimens were loaded until target damage levels, damage level II (Minor) and IV (severe) and re-loaded until failure after repair by general repair practice mentioned above. The repair work is carried out using the method shown in Figure 7.

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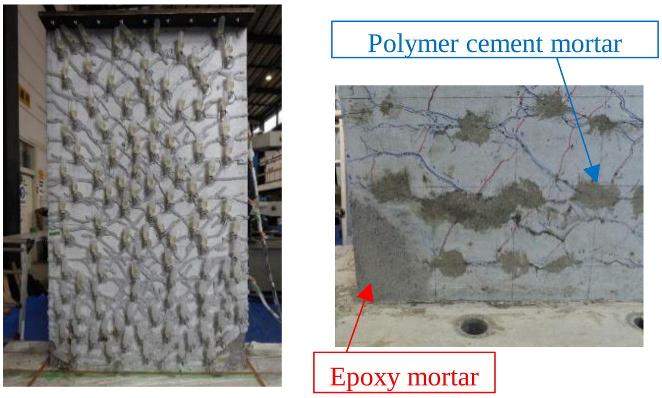
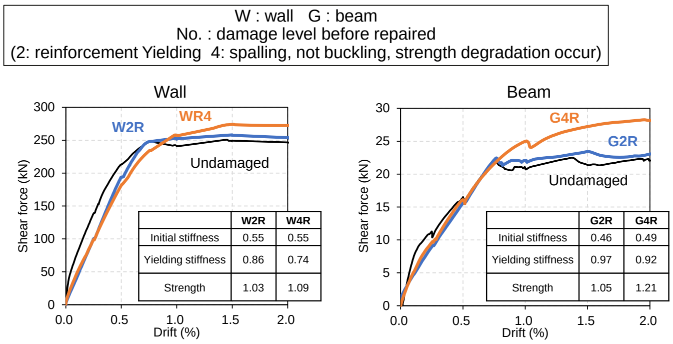
Backbone curves obtained from the experiment are shown in Figure 8 together with capacity recovery factors of initial and yielding stiffness and strength. Major findings from the experiment are summarized as follows.



(a) Epoxy injection (b) Mortar patching

Figure 7: Popular repair methods in Japan

- Initial stiffness recovery of 0.45 to 0.55 of the original members was achieved, regardless of the initial damage level.
- Secant stiffness at the yielding point of the repaired members recovered 0.85 to 0.95 in moderately damaged specimens while in severely damaged specimens, recovery was 0.75 to 0.90.
- Structural strength of the repaired members was found to be equivalent to that of the original members in moderately damaged cases and 1.1 to 1.2 in severely damaged cases.
- Energy absorption capacity recovery was more than 0.8 in moderately damaged members and more than 0.4 in severely damaged members.



	W2R	W4R
Initial stiffness	0.55	0.55
Yielding stiffness	0.86	0.74
Strength	1.03	1.09

	G2R	G4R
Initial stiffness	0.46	0.49
Yielding stiffness	0.97	0.92
Strength	1.05	1.21

(a) flexural wall *(b) flexural beam*

Figure 8: Backbones and recovery ratios flexural RC wall and beam (damage level II and IV)

See the reference Miura K. et al (2023) for more details.

An evaluation of seismic performance recovery of partially repaired component shown in Figure 3. Figure 3 is also needed to expand options of repair strategies. However, there is no data regarding partially repaired components and so it will be a study in the future.

4 EVALUATION PROCESS OF REPAIR COST AND ECONOMIC LOSS

4.1 Evaluation of repair cost

In this chapter, the policy for evaluation of repair cost of damaged buildings is explained. Currently, in Japan, there is no established framework regarding repair cost of both structural and non-structural components. On the other hand, in P-58 of FEMA (2018) in U.S., a database of fragility curves, repair costs, and repair time is provided for each component (structural, non-structural, equipment). Therefore, in this study, the repair cost is estimated using the FEMA P-58.

FEMA P-58 provides the PACT software to calculate repair cost and time. Summary of the calculation method is shown below and in Figure 9.

1. Damage level for each component was determined by inputting the geometry of the building model and the response values obtained from the seismic response analysis.
2. Repair cost and repair time corresponding to the damage level for each component is outputted. As the output comes in form of a probability distribution calculated by Monte Carlo simulation, mean value of cost and time were used as expected value.

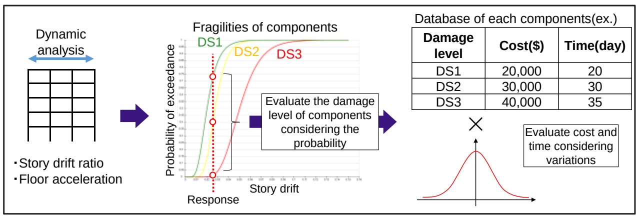


Figure 9: Process of evaluation of repair cost and time in PACT

3. Repair cost of a building was calculated as the sum of expected cost of all components.

4.2 Evaluation of economic loss

Economic loss, which is also related to building resilience assessment, is an indicator to evaluate the disadvantages of unavailability of a damaged building due to earthquake and during restoration. There are various parameters that could be considered to evaluate economic loss, such as a downtime when a building is out of service, benefits and income that should have been gained during the restoration, and the number of people who cannot use the building. In this study, economic loss is defined as rent that should have been earned by a building owner during the downtime, which can be calculated as money simply if the building is used as an office, residential dwelling, or commercial facility. Thus, economic loss is defined as rent multiplied by downtime. Downtime is the period during which the building cannot be used due to restoration. It can be calculated based on the database of repair time in FEMA P-58 as described in 4.1 so the calculation process is the same as the repair cost.

Since repair times are outputted for each component by PACT, it is necessary to convert the repair time of components to the repair time in a certain area which people could not use (e.g., each floor, tenanted space). The conversion method is shown below and in Figure 10.

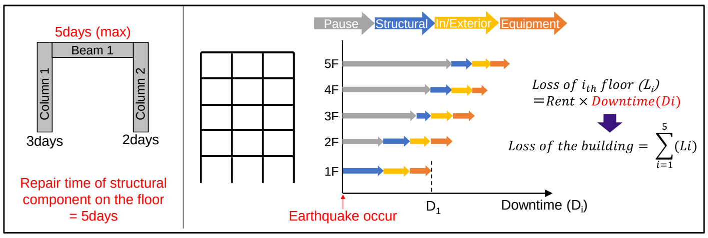


Figure 10: Calculation method of economic loss

1. All components to repair are categorized into three categories, structural components, interior/exterior non-structural components, and equipment.
2. For each of these three categories, the maximum repair time of each component in the category on the floor is used as the repair time of the category.
3. The downtime of the floor was calculated as the sum of repair time of each category. However, since it is actually unlikely that repair work will be done on all floors at the same time, it was assumed that work

on each category would not begin until the work on one floor below was completed (represented by the ‘pause’ in the Figure 10).

4. Loss of each floor (L) was calculated by multiplying the rent of the floor by the downtime (D).
5. Total loss of the whole building was calculated as the sum of the loss of each floor.

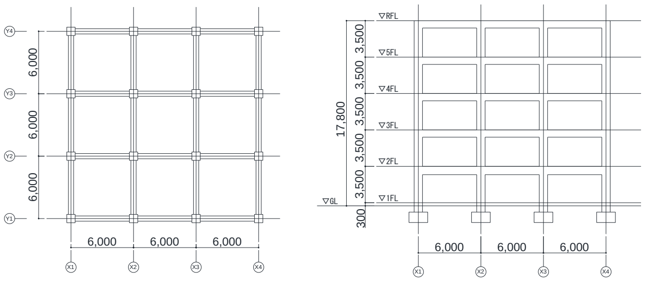
5 CALCULATION OF RREPAIR INDEX APPLICATION STUDY

In this chapter, a prototype five-storied frame structure is selected for an application example of evaluation of Repair Index. And using RI, the most cost-effective repair strategy is discussed.

5.1 Prototype structure

A five-storied frame structure assumed as an office building, as shown in Figure 11, is selected as an application example. The structure was designed to form a beam-yielding sway mechanism and satisfied minimum requirements of horizontal strength and ductility according to the Japanese Seismic Design Code, BCJ (2016). Cross-sectional details are shown in Table 2.

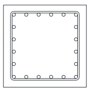
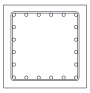
As described in Chapter 4, this paper considered structural components (beams, columns etc.), non-structural interior or exterior components (external walls, internal walls, ceilings etc.) and equipment (elevators, pipes, air handling units, lightnings etc.) as elements of a building. In this example, it is set up with components that would be installed in a typical office shown in Table 3.



(a) Floor plan (b) Elevation

Figure 11: Plan of a 5-story RC building (mm)

Table 2: Lists of components of the target building.

Column		
Cross-section	1〜3F 	4〜5F 
Size(mm)	800 × 800	800 × 800
Longitudinal bar	20-D32	20-D32
Hoop	2-D16@150	2-D13@150
Compressive strength(N/mm^2)	24	24

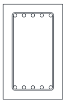
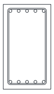
Beam		
Cross-section	2〜4F 	5〜RF 
Size(mm)	500 × 800	400 × 700
Longitudinal bar	5-D29	5-D25
Stirrup	2-D10@100	2-D10@100
Compressive strength(N/mm^2)	24	24

Table 3: Lists of building components calculated for repair cost and time.

Category	Name
Structural	Column-beam Joint
Non-structural	Curtainwall
	Wall partition
	Stair
	Access floor
	Suspended ceiling
	Lightning

Category	Name	Name
Equipment	Elevator	HVAC fan
	Portable	Air handling unit
	Chiller	Fire sprinkler
	Cooling tour	Transformer service
	HVAC ducting	Motor control center
	Hvac drops	Low voltage switchgear
	Hvac box	Distribution panel

5.2 RI evaluation procedure

5.2.1 General

An outline of the RI evaluation procedure is illustrated in Figure 12. Firstly, seismic response analysis of the frame model was performed using a selected seismic ground motion (1st earthquake) and damage level of all the structural elements was identified. The modeling characteristics components of the structure were then modified by capacity recovery factors Φ from section 3.2 according to the individual damage level and then seismic capacity α, repair cost and economic loss of the 1st restoration are evaluated by the method proposed in Chapters 3 and 4, respectively. Then, additional seismic response analyses with different level of ground motion (2nd earthquake) were performed for repaired models to quantify the expected values of repair cost and economic loss of the 2nd repair in the same way.

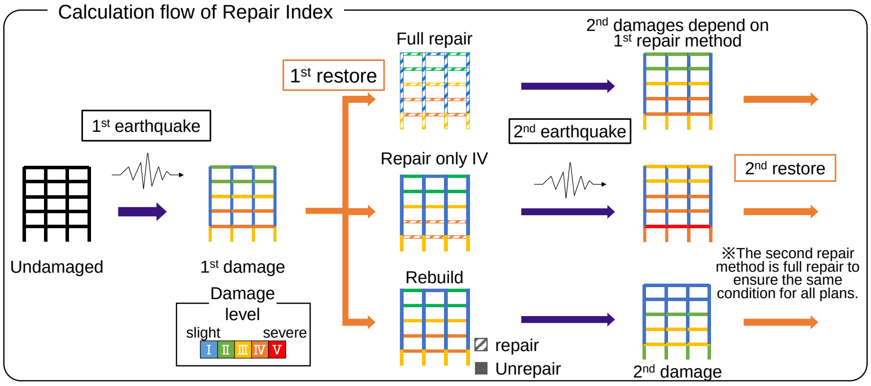


Figure 12: Process of RI evaluation

5.2.2 Input ground motion

An artificial ground motion that matches the shape of the Japanese design response spectrum was selected as the input ground motion. Intensity for the 1st earthquake was selected so that moderate damage is induced into the target structure. From time-history analysis and damage classification of JBPDA (2015), damage levels I to IV were distributed in the structure as shown in Figure 13. In the analysis after repair (2nd earthquake), 5 earthquake intensity which are a little smaller than the 1st one was considered possible over the building's lifetime.

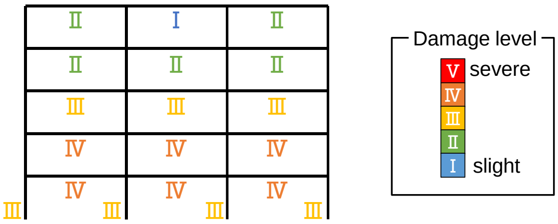


Figure 13: Damage levels after 1st earthquake

5.2.3 Selection of repair cases

Two damage-level based selection policies were investigated among possible alternatives in this study. One method is to start repairing components from major damage to minor damage. The other method is to repair from minor damage to major damage.

5.2.4 Repair Index calculation based on repair cost and economic loss

The Repair index was calculated using Equation (1). In this calculation, it is noted that similar to the first repair in Figure 12, the repair cost and economic loss after the second earthquakes would depend on the repair strategy chosen for the 2nd repair. However, to allow for a meaningful comparison between the effectiveness of the 1st repair strategy, it was assumed that the 2nd repair would employ a constant 'full repair' strategy for all damaged components. The summation of costs and losses due to the 1st and 2nd repairs were summed up as expected total required cost over the entire lifecycle. Since the cost of the second repair was then taken as the expected value, the probability of occurrence corresponding to the magnitude of the seismic motion was multiplied by the cost and loss, and the sum of them was used as the expected total cost of the 2nd repair. The probability of occurrence was based on the hazard for Tokyo.

$$\boldsymbol{RI} = \frac{\boldsymbol{Total\ required\ cost_{Repair}}}{\boldsymbol{Total\ required\ cost_{Reconstruction}}} = \frac{(\boldsymbol{Cost_{1st}} + \boldsymbol{Loss_{1st}}) + (\boldsymbol{Cost_{2nd}} + \boldsymbol{Loss_{2nd}})}{(\boldsymbol{Cost_{Reconst.}} + \boldsymbol{Loss_{Reconst.}}) + (\boldsymbol{Cost_{Reconst.2nd}} + \boldsymbol{Loss_{Reconst.2nd}})} \tag{1}$$

cost of 1st restore cost of 2nd restore(expected value)

$^*Cost$ ･･･Repair/Reconstruct cost $Loss$ ･･･economic loss

5.3 RI evaluation procedure

For the two repair plans made according to the policy shown in 5.2(3), seismic capacity indices defined in 3.1 and cost were calculated. The relationships between the seismic capacity index after repair and total required cost are shown in Figure 14. As shown in Equation (1), the total required cost was calculated as the sum of definite repair cost and economic loss by the first earthquake and the expected repair cost and economic loss in the possible future earthquakes (2nd earthquake). In Figure 14, individual required cost was shown on the left and the total required cost was shown on the right. In this calculation of 2nd required cost, the hazard in Tokyo was used. This figure confirms the trend that the more costs are funded in the first repair, the lower the cost in the second repair, and when summed up, we find cases where the total future loss is lower than the full repair.

The calculation results of Repair Indices of different repair cases are compared in Figure 15. Here, the reconstruction cost in the denominator of the formula in Figure 9 was calculated as the sum of new construction cost and demolition cost. New construction cost and demolition cost were calculated by multiplying typical construction cost per m2 shown in Sadamoto M. et al. (2021) and the total area of the target building. The results show that repair is more efficient than reconstruction for case study example since RI is less than 1 in all cases. This is because damage level of the structure by the 1st earthquake is moderate, or the size of building is small. As can be seen from Figure 15, RI for all the "limited repair" cases

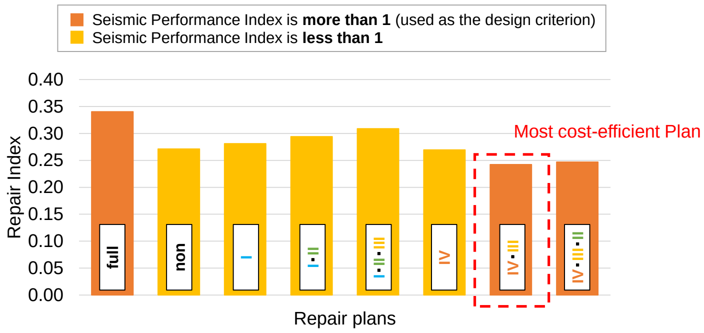


Figure 15: Calculation results of Repair Index

are lower than RI for the “full repair” strategy. It suggests that repair is not necessary to all the damaged elements and selected repair is reasonable in terms of cost effectiveness.

Note that seismic capacity of a structure is necessary to satisfy requirement of seismic code even after repair. In Figure 15, hatched cases have less than 1.0 of seismic capacity indices because the Japanese Building Code requires a minimum of 1.0. It suggests that to repair elements of damage level III or higher is the most efficient strategy enough to satisfy design capacity requirements. Moreover, limited repair with damage level III and IV (as opposed to full repair) results in minimum RI, therefore the most efficient repair strategy among studied cases.

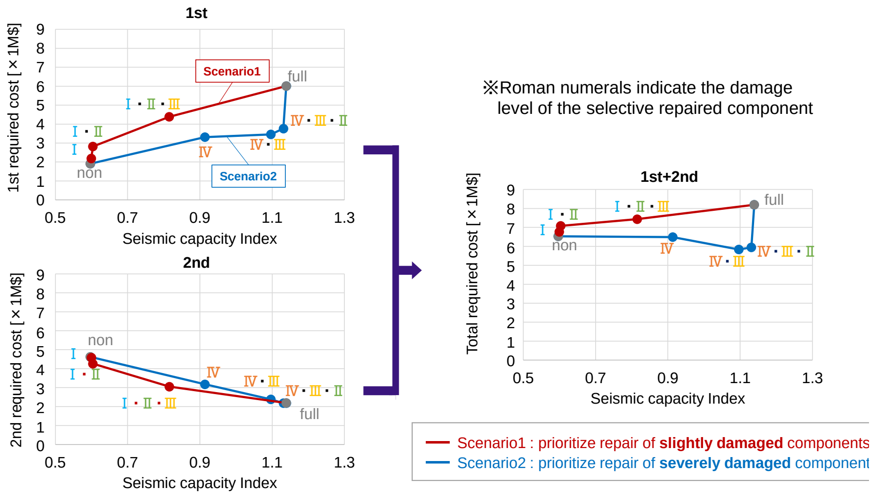


Figure 14: Relationships between seismic capacity index and cost

Thus, the evaluation based on Repair Index enables us to find the most reasonable recovery strategy for damaged buildings considering both repair costs and economic losses quantitatively.

6 CONCLUSIONS

This study proposes a repair index (RI) to plan rational strategy of repair and restoration of earthquake-damaged buildings, balancing seismic performance recovery and economic loss.

(1) The Repair index comprises the degree of seismic performance recovery, repair costs, and economic losses resulting from repair work. To calculate repair costs and economic losses, expected losses from future earthquakes are considered in addition to the earthquake that has already occurred. This approach enables more effective restoration solution.

(2) The Repair index was used to evaluate several selective repair policies for a five-storey trial design RC building, assuming earthquake damage. The results showed that repairing the most damaged members first, without repairing minor damage (damage levels I and II), was the most effective strategy.

(3) The proposed method's generalization can contribute to the development of plans for the efficient use of limited time and cost in earthquake restoration for RC buildings of different usage, economic and damage levels, while meeting the required seismic capacity.

7 ACKNOWLEDGEMENT

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