DAMAGE INDEX FOR PERFORMANCE EVALUATION OF FUNCTIONAL MAINTENANCE AFTER EARTHQUAKES

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Abstract

In particular, when designing a high-rise building, it is recommended that the entire collapse mechanism (i.e. strong column-weak beam mechanism) be planned and sufficient safety of the building be ensured by allowing earthquake damage to spread throughout the building and by ensuring that the energy generated by the earthquake is absorbed evenly by the entire building. However, it is a matter of serious concern that the damage on every floor causes extensive spreading of the area to be restored, greatly increases the repair cost, and lengthens the restoration period, making functional recovery difficult.

Developing design methods that consider the safety and post-seismic functional maintenance of buildings is required to reduce damage to buildings and minimize damage to society from major earthquakes. The authors in this study define the severity of the damage as that which repair time is becoming relatively large. An “ideal repair time (IRT)”, which is an index used to relatively evaluate the severity of the damage, is proposed from the viewpoint of functional maintenance necessary for such design.

Many factors influence the repair time other than the damage state. These factors include the social and surrounding environments, number of engaged workers, work proficiency and so on. The repair time would still vary when these factors are different even if the damage state is the same. The IRT is a damage evaluation index that targets only the damage state (i.e., amount, extent, and concentration of the damage) by eliminating influences of factors other than the damage state.

The IRT has the following features:

1. The analysis based on the IRT can clarify the influence of the damage state (i.e., amount, extent, and concentration of the damage) on the dysfunctional time of the building. The IRT allows structural designers to investigate the validity of planed collapse mechanism, assumed deformation levels, strength, and stiffness given to the building from the viewpoint of functional maintenance.

2. Various types of damage occur in the building, such as the damage to structural components, nonstructural components, and items of equipment. How to express the severity of these damages is different for each. The IRT uniformly evaluates the severity of the different types of damage, and enables a relative comparison of damage-resistant performance of buildings, where different types of damage have simultaneously occurred. The IRT allows us to make a seismic design to secure the damage-resistant performance from the viewpoint of the functional maintenance.

3. The IRT aims to relatively evaluate the dysfunctional time caused by the damage and allows ordinary people who do not have special knowledge of structural engineering to easily understand the relative difference of the severity of the damage and the level of the damage-resistant performance given to the building.

Keywords: damage evaluation index, damage-resistant performance, functional maintenance, repair time

1. Introduction

The need for seismic design methods aiming to secure the post-seismic functional maintenance is becoming more recognized because of recent seismic damages to buildings. The Building Research Institute and Japan Structural Consultants Association has introduced evaluation methods aiming to secure post-earthquake functional use based on three performance ranks determined by the damage state in each component [1].

This study attempts to propose an index to evaluate the damage-resistant performance of buildings from the perspective of the functional maintenance. The damage-resistant performance in this study means the ability to prevent the occurrence of the damage and functional inhibition caused by an earthquake. Developing an index to indicate the damage severity is required to evaluate the damage-resistant performance.

Note that the damage index discussed in this study is for the functional maintenance evaluation and not for the safety evaluation (e.g., damage degree of safety in "Guideline for Post-earthquake Damage Evaluation and Rehabilitation" [2]). The terms "damage degree", "amount of damage", and "loss" are defined herein upon discussing the damage index.

Damage degree is defined in relation to the amount of damage and scale of damage as follows:

$$\text{Amount of damage} = \text{damage degree} \times \text{scale of damage.} \qquad (1)$$

The amount of damage is the engineering amount described as the following formula in relation to the loss (in Yen) caused by the damage:

$$\text{Loss} = \text{amount of damage} \times \text{unit price} \qquad (2)$$

where the unit price is the loss per unit amount of damage, and the scale of damage is the engineering amount indicating a size of the object, where the damage has occurred. The damage degree is the amount of damage per unit scale of damage and an important engineering amount upon designing buildings with the aim of reducing loss.

2. Severity Evaluation of Damage from the Perspective of Functional Maintenance

The repair time is one of the most important factors to consider when evaluating the severity of the damage from the perspective of functional maintenance. This study defines the severity of the damage as that wherein the repair time is becoming relatively large.

Clarifying the meaning of the index in this study is important by distinguishing the factors that are to be and not to be evaluated on developing the damage index.

The repair work is generally composed of some kinds of works. First, the working time of each work is calculated. The network time schedule is then created considering the order of the works and whether they can be simultaneously performed. Furthermore, the network time schedule is investigated by making a graph of changes in the number of workers and the amount of materials to be used during the work period.

The nine following factors affect the repair time: I) amount of damage; II) extent of damage; III) concentration of damage; IV) difference in work efficiency that resulted from adopted methods and worker proficiency; V) days when workers cannot work because of holidays, rainfalls, and snow falls; VI) approach to order of work and work performed simultaneously; VII) limitations on the number of workers and the amount of materials, which can be thrown into the work depending on the contractor's working system; VIII) limitation on the working time period and adopted repair methods depending on the surrounding environment; and IX) limitation on the number of workers and technicians and the amount of materials depending on the social environment.

Factors I, II, and III are the influence factors related to the damage state. Factors IV to IX are those not related to the damage state. The repair time would change if factors IV to IX are different even if the damage state is the same (i.e. I, II, and III are the same).

Factors IV to IX, which are factors other than the damage state, are not subject of the evaluation because this study aims to propose an index to evaluate the damage-resistant performance. From the next chapter, the authors attempt to build the index to relatively evaluate the severity of the damage based on the repair time calculated from Factors I, II, and III related to the damage state.

3. Damage Evaluation of Components

As mentioned in the previous chapter, the formulation of the time schedule is composed of two steps, which are evaluations of the work time for each work and of the whole construction period based on it. The evaluation of the damage-resistant performance shall also be conducted using two steps of the damage evaluation of components and of the whole building based on it.

3.1 Time damage and amount of time damage

3.1.1 Time damage

The amount of time damage to a component *i* (hereinafter referred to as ${}_{A}Di$) is defined by the following formula:

$$ {}_{A}D_i = td_i \times a_i \tag{3}$$

where tdi is the time necessary for repairing a component *i*, and a_i is the floor area necessary for the repair work of component *i* (hereinafter referred to as the repair work area).

The amount of time damage is the amount of functional damage caused by the damage to the component and is described as the product of the dysfunctional time multiplied by the dysfunctional floor area. If a_i is regarded as one of the indices indicating the scale of the damage, tdi can be regarded as the damage degree in a sense by the comparison of the abovementioned formula and Eq. (1). The time necessary for repairing the component is referred to herein as the time damage of the component.

The time damage of the component *i*, namely tdi, is defined by the following formula:

$$ td_i = \frac{L_i}{m_M} \tag{4}$$

where Li is the labor amount (man-day) necessary for repairing component *i*; m_M is the number of maximum workers who can be thrown into the work; and m_M is calculated from the repair work area a_i using the following formula:

$$ m_M = a_i \times k \tag{5}$$

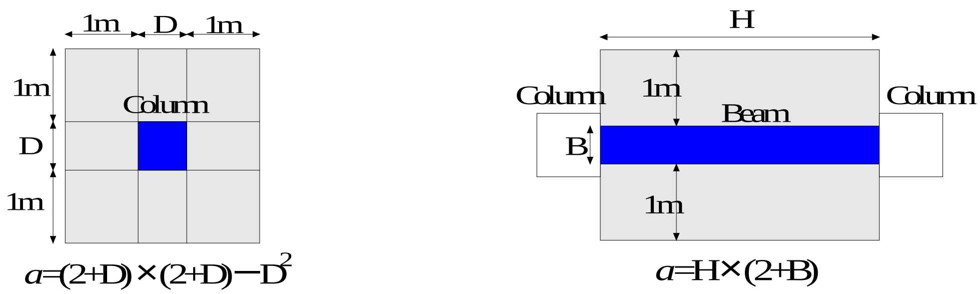
where k is a constant determining the maximum number of workers thrown into the work per repair work area of 1 m^2. Although determining the exact value of k is difficult, the authors assume that one worker per floor area of 2.0 m^2, which is the product of the width of 2 m, where a worker opens his arms multiplied by the distance from the object of 1 m, is the maximum number of workers thrown into the work. For convenience, the authors adopt the value of k = 0.5 person/m^2 for all the objects to be evaluated because the value of k does not influence the relative comparison of the damage-resistant performance.

The time damage is the actual time from the start to the end of the repair work of the component, which is performed by the maximum number of workers, who can be thrown into the work. Note that this time damage does not include the preparation time (e.g., material procurement and temporary installation).

3.1.2 Repair work area

The work area needs to be secured around the component to conduct the repair work. The “Estimation manual for repair work of public building” [3] describes that on performing the repair work, the work area should be secured by installing temporary partitions 1 m apart from the object to be repaired. Herein, the authors regard the repair work area a_i as an area surrounded by connected cross lines drawn parallel to and 1 meter apart from the object surface based on and referring to the abovementioned description. In principle, this area does not include the area where the object to be repaired exists. Fig. 1 shows the calculation examples of the repair work areas a_i

of column and beam components. The beam component is different from the column component such that its work area is not surrounding the four sides because both edges are connected to the columns and includes the floor area beneath the component.



(1)Repair work area of column a (m^2)　　　(2) Repair work area of beam a (m^2)

Fig. 1 – Repair work areas of column and beam

3.1.3 Calculation of the required labor amount *L*

The required labor amount *Li* for component *i* is calculated using the following formula by summing up the labor amounts in each damage that occurred:

$$L_i = \sum (Q_j \times \beta_j) \tag{6}$$

where β is the repair time coefficient, and Q is the amount of repair work. β of each repair work of damage that occurs in structural component, nonstructural component, and items of equipment is surveyed in the research project of the Building Research Institute [4, 5] and collected in the repair evaluation database. The β of three types of damage (i.e., width of a crack "less than 0.2 mm" and "0.2 mm or more" and "spalling" of concrete) in the database is shown in Table 1 as an example. Eq. (6) is concretely described as follows:

$$L_i = L_A(m) \times \beta_A + L_B(m) \times \beta_B + F(m^2) \times \beta_C \tag{7}$$

Table 1 – Repair time coefficient for cracks and spalling of concrete

Types of damage	Amount of repair work	Repair time coefficient β
Width of crack less than 0.2 mm	Length of crack L_A(m)	β_A=0.03
Width of crack 0.2 mm or more	Length of crack L_B(m)	β_B=0.24
Spalling of concrete	Area of spalling F(m^2)	β_C=7.1

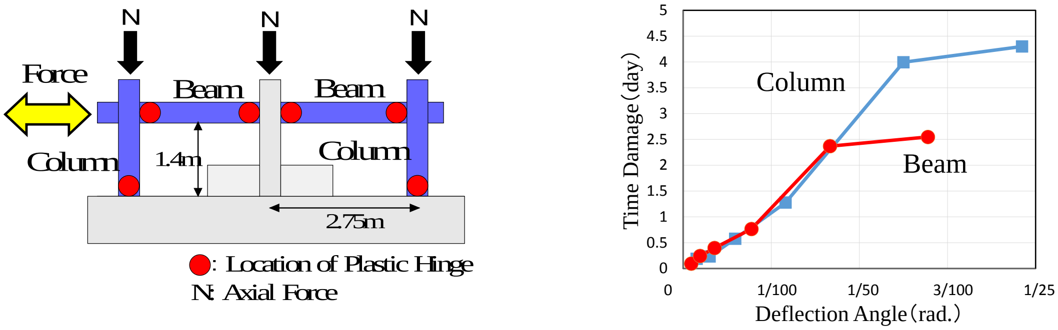
3.2 Damage-resistant performance evaluation of flexural failure column and beam

1-story, 2-span frame specimen shown in Fig.2(1) was constructed and tested[6]. Table 2 presents the dimensions of the members. Fig. 2(2) shows the time damage *tdi* of flexural failure beam and column in the frame, calculated by using Eq. (4), (5), and (7), in which full-scale, doubled dimensions are used to evaluate *tdi*. Fig. 2(2) shows that both the flexural failure beam and column need a 1.0 and 2.5 to 3 day-repair time when the deflection angle is 1/100 and 1/50, respectively.

Table 2 – Specifications of members

	Width×Depth (mm×mm)	Clear Span (mm)	Axial Force(kN) (Axial Force Ratio)	Longitudinal Reinforcement			Shear Reinforcement			Concrete Strength
				Diameter＆Quantity	p	σy	Diameter＆Spacing	p	σy	
Beam	300×400	2350	0 (0.00)	top:6-D19 bottom:4-D19	1.43% 0.96%	382.0 (N/mm^2)	4-D6 @50	0.83%	343.6 (N/mm^2)	34.7 (N/mm^2)
Column	400×400	1400	500 (0.09)	16-D16	1.05%	384.1 (N/mm^2)	4-D10 @50	1.43%	343.6 (N/mm^2)	34.7 (N/mm^2)

σy:Yield Strength, p:Reinforcement Ratio



(1)Frame Specimen (2) Time damage of flexural failure beam and column

Fig. 2 – Evaluation of damage-resistant performance of flexural failure beam and column

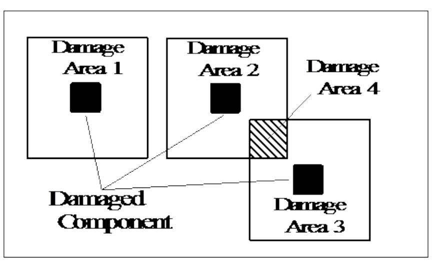
3.3 Area time damage td_A

The existence of a component with the time damage tdi means that the repair work area a_i cannot be used during tdi because of the repair work. Unusable areas increase if there are multiple components to be repaired. Furthermore, the repair time lengthens, where their work areas overlap each other. Such time necessary for the repair work shown in a plan view shall be called the area time damage td_A distribution. The td_A of each point on the plan view is calculated using the following formula:

$$td_A = \sum_{i=1}^{n} tdi \tag{8}$$

where n is the number of members which repair work area includes the point.

Fig. 3 schematically shows the td_A distribution in case three damaged components exist in the building. Four areas in which the td_A is uniform appear because of overlap of repair work areas. Each area is herein referred to as the “damage area”. The area time damage td_A and its area (hereinafter referred to as ${}_RA$) of the four damage areas are shown in the same figure.



	td_A	${}_RA$
Damage Area 1	td_1	a_1
Damage Area 2	td_2	a_2
Damage Area 3	td_3	a_3
Damage Area 4	td_2+td_3	a_{23}

Fig. 3 – Distribution of area time damage td_A

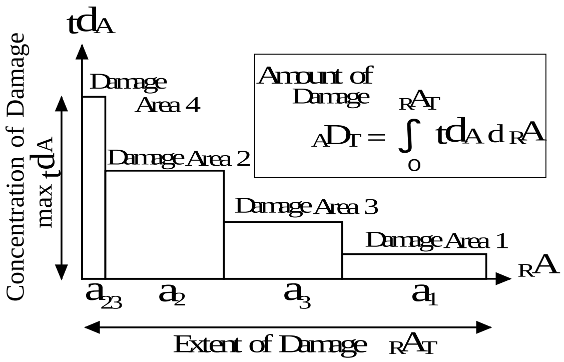
Fig. 4(1) sets the ${}_RA$ to the horizontal axis and puts the td_A of each damage area in a descending order. The amount of the time damage ${}_AD$ is calculated by integrating this relation of td_A and ${}_RA$ with the ${}_RA$ (Eq. (9)).

$${}_AD = \int_0^{{}_RA} (td_A)\, d{}_RA \tag{9}$$

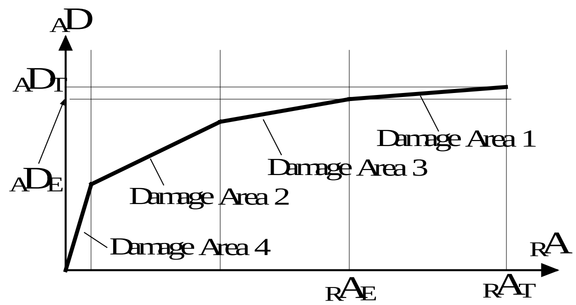
The relation of ${}_AD$ and ${}_RA$ shown in Fig. 4(2) is obtained by setting the ${}_RA$ to the horizontal axis and the ${}_AD$ to the vertical axis. The total of each damage area ${}_RA$ shall be called the total damage area ${}_RA_T$. The relation of td_A and ${}_RA$ shown in Fig. 4(1) is integrated with 0 to ${}_RA_T$ (Eq. (10)), and the value is then called the total amount of time damage ${}_AD_T$.

$${}_AD_T = \int_0^{{}_RA_T} (td_A)\, d{}_RA \tag{10}$$

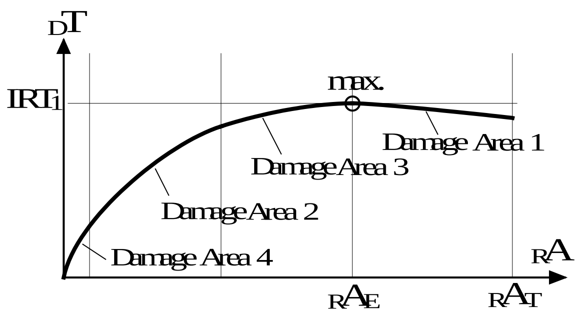
where ${}_AD_T$ is equal to the total of ${}_ADi$ shown in Eq.(3).



(1)Relation of ${}_td_A$ and ${}_RA$



(2)Relation of ${}_AD$ and ${}_RA$



(3) Relation of ${}_DT$ and ${}_RA$

Fig. 4 – Calculation Procedures of Ideal Repair Time

4. Ideal Repair Time (IRT)

The amount of damage caused by the building dysfunction is defined by the following formula:

$$\text{Amount of functional damage} = \text{dysfunctional time} \times \text{dysfunctional floor area} \tag{11}$$

The loss (opportunity loss) that resulted from the building dysfunction is calculated by the following formula using the functional damage amount.

$$\text{Opportunity loss} = \text{amount of functional damage} \times \text{unit price of floor} \tag{12}$$

Regarding the dysfunctional area as the scale of the damage and comparing these formulae and Eq. (1) and (2) show that the dysfunctional time is a kind of damage degree. This chapter discusses "ideal repair time (IRT)", which is the damage degree to function of building.

The term "ideal" herein means not the best thinkable state but the state meeting a certain stipulated condition. The IRT is the repair time eliminating the influence by Factors IV to IX other than the damage state among the factors influencing the repair time mentioned in Chapter 2 as follows:

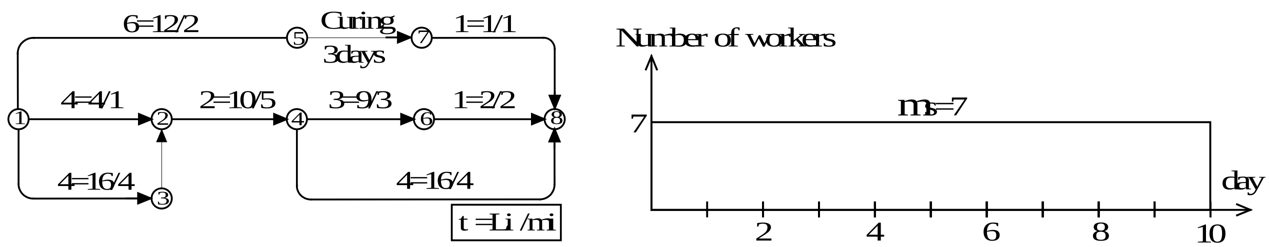
IV: To set the standard repair method and work efficiency
V: No days when workers cannot work because of holidays and climate
VI: The number of workers during the work period is the standard number of workers (described in 4.1.1) and fixed, and the idealized process, in which Total Float = Free Float = 0, is assumed
VII & VIII & IX: No limitations

The repair time determined by the amount of damage ${}_AD_T$ and the extent of damage ${}_RA_T$ shown in Fig. 4(1) is defined as IRT_1 and determined by the damage concentration (maximum td_A) as IRT_2. It can be said that IRT_1 and IRT_2 are repair time determined by factors I, II, and III, respectively. The IRT is determined by the larger one between IRT_1 and IRT_2.

4.1 IRT determined by the damage amount and extent

4.1.1 Formulating repair time ${}_DT$

The authors assume that the number of workers during the work period is the standard number of workers m_s and is fixed as shown in Fig. 5(2), and that both total float and free float are zero in all paths. In such time schedule, the lengths of all the paths are the same as shown in Fig. 5(1).



(1) Network time schedule (2) Number of workers thrown into the work

Fig. 5 – Idealized Process

In Fig. 5(1), amount of labor Li, number of workers m_i and working time ($Li/\ m_i$) of each job are shown. The time schedule in Fig.5 (1) shows that the work period is 10 days (e.g., 4 + 2 + 3 + 1 = 10 at the path of 1-2-4-6-8). However, the work period can be calculated from the total labor amount $L(=\sum Li)$ using Eq. (13) without creating the time schedule shown in Fig. 5(1) for such an idealized case. In the example of Fig. 5(1), L = 70 man-day and m_s = 7 persons leads to 10 days (= 70/7).

$$ {}_DT = \frac{L}{m_s} \qquad (13) $$

Note that the work period can be calculated without including the curing time because the workers are assumed to constantly perform some work even during the curing time.

In addition, L can be described as follows using the amount of time damage ${}_AD$:

$$ L = {}_AD \times k\,. \qquad (14) $$

The standard number of workers m_s is thought to be an adequate number for the damage area a_i in terms of economy and accuracy of the repair work. The following relation is assumed between ${}_RA$ and m_s:

$$ m_s = \lambda \times {}_RA^{\gamma}\,. \qquad (15) $$

The maximum number of workers, who can be thrown into ${}_RA$ is as follows from Eq. (5):

$$ m_M = {}_RA \times k \qquad (16) $$

Where m_M is the maximum number of workers, and m_s and m_M are in a relation of $1 \le m_s \le m_M$.

The following is obtained when ${}_RA$ is deleted from Eq. (15) using Eq. (16):

$$ m_S = \frac{\lambda}{k^{\gamma}} m_M{}^{\gamma} \qquad (17) $$

When $m_M = 1$, $m_S = 1$, thus:

$$ m_s = m_M{}^{\gamma} = k^{\gamma} \cdot {}_RA^{\gamma} \qquad (18) $$

Accordingly, m_s is determined when γ is settled because k = 0.5 is already assumed.

Sasama[7] conducted a survey on the standard number of workers m_s for carpenter work, plaster, and earth work to 10 experts. As a results, the values of γ in Eq.(15) were estimated to be 0.64, 0.48, and 0.40 for the carpenter work, plaster, and earth work, respectively. In the present study, γ is assumed to be 0.5. Given that γ = 0.5, the repair time ${}_DT$ is calculated by the following formula using Eq. (13), (14), and (18):

$$ {}_DT = {}_AD\sqrt{\frac{k}{{}_RA}} \tag{19} $$

4.1.2 Effective repair work area ${}_RA_E$

Fig. 4(3) shows the relation of ${}_DT$ and ${}_RA$ schematically calculated from Eq. (19). ${}_DT$ does not always show a monotonic increase and may decrease altogether with an increase of ${}_RA$ as will be shown in Chapter 5. Fig. 4(3) shows that ${}_DT$ increases in the damage area of 4, 2, and 3 but decreases when the damage area 1 is added. This happens because the increase of m_s caused by the increase of ${}_RA$ becomes larger than the increase of ${}_AD$.

However, the repair time of damage areas 4, 2, 3, and 1 cannot be shorter than the repair time of damage areas 4, 2 and 3 at the actual repair work. In fact, additional workers are thrown into the work in damage area 1. And the completion of the work during the repair work of damage areas 4, 2, and 3 is then performed. In other words, ${}_AD$ and ${}_RA$ of damage area 1 do not influence the increase in ${}_DT$.

The authors calculate IRT_1 by the following formula using an effective damage area ${}_RA_E$, which is calculated by subtracting ${}_RA$ of damage area 1 from ${}_RA_T$, and the amount of time damage at that time (hereinafter referred to as the effective amount of time damage, ${}_AD_E$). IRT_1 calculated by Eq. (20) is the maximum value of ${}_DT$ in the relation of ${}_DT$ and ${}_RA$ (Fig. 4(3)):

$$ IRT_1 = {}_AD_E\sqrt{\frac{k}{{}_RA_E}}. \tag{20} $$

4.2 IRT determined by concentration of damage

Herein, the authors think about a case, where the repair work of a certain area becomes a critical path and determines the repair time. This case is where the maximum value of td_A shown in Fig. 4(1) (i.e., td_A of damage area 4) is very large, and the work period of this damage area determines the whole repair period.

In the case where the repair time is determined by the amount and the extent of damage considered in the previous section, the curing time in each repair work needs not to be considered. However, the curing time needs to be included in this case. The ideal repair time IRT_2 in this case is defined by the maximum value of the partial repair time ${}_PT$ calculated by Eq. (21) as follows:

$$ {}_PT = {}_td_A + \sum_{i=1}^{n_y} y_i \tag{21} $$

$$ IRT_2 = \max\{{}_PT\} \tag{22} $$

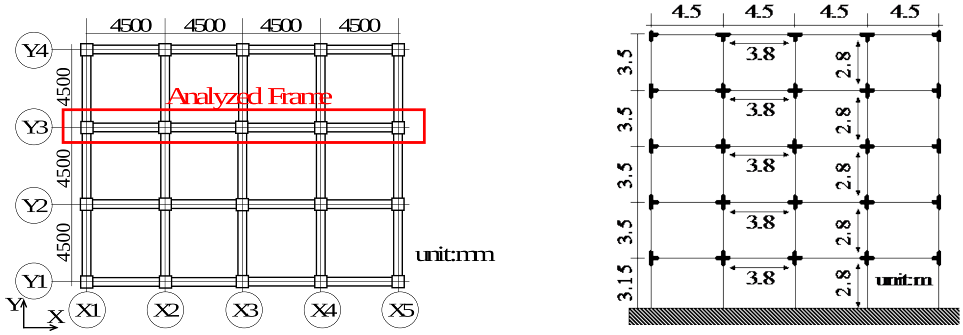
where n_y is the number of types of curing necessary for the partial repair, and y_i is the curing time of the ith curing type.

IRT_2 is the repair time when a part with a concentrated damage is repaired by the maximum number of workers within the shortest time.

5. Damage-resistant Performance Evaluation of Building

5.1 Building subject to analysis and analytical method

The subject building is a 5-story RC building, as shown in Fig. 6. Nonlinear push-over analysis was performed, in which *Ai* distribution was used for lateral force distribution. The analysis was terminated when the drift angle of any story reached 1/50. And, the damage-resistant performance evaluation at the time was conducted. A structural calculation software (i.e., SNAP) was used for the analysis. The column and beam members were modeled by line elements with nonlinear springs. Table 3 shows the sectional dimensions of the members.



(1) Plan view (2) Elevation

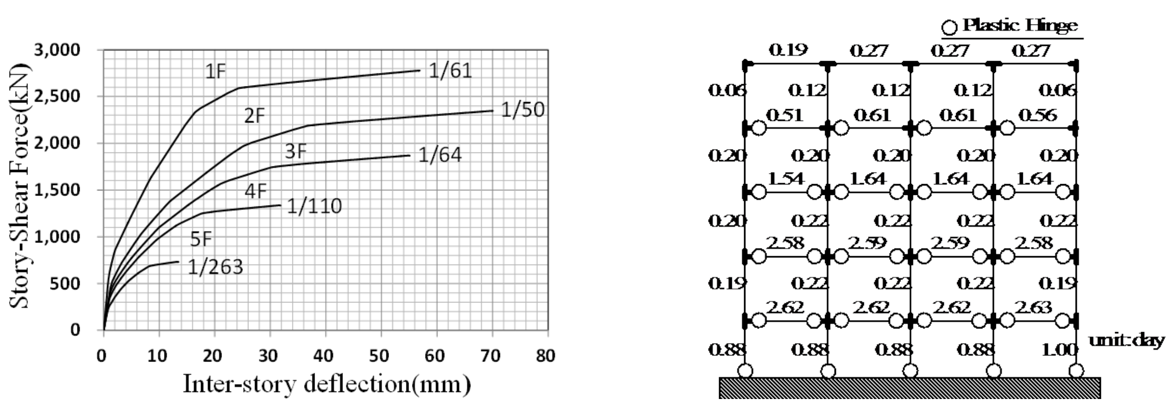
Fig. 6 – Subject building

Table 3 – Column and beam dimensions in the analyzed frame and tested frame

	Frame Specimen *		Subject Building	
	Column	Beam	Column	Beam
Width (m)	0.8	0.6	0.7	0.5
Depth (m)	0.8	0.8	0.7	0.7
Length (m)	2.8	4.7	2.8	3.8
Ratio of width to depth	1	0.75	1	0.71
Ratio of length to depth	3.50	5.88	4.00	5.43
		* full-scale		

5.2 Damage state and time damage

Fig. 7(1) shows the relation between the story-shear force and the inter-story deflection obtained from the analysis. The deflections of the 1st, 2nd, and 3rd stories are large. Fig. 7(2) shows the location, where the plastic hinges are formed. The plastic hinges are formed at the bottom end of the 1st story column and both ends of the beams of the 1st, 2nd, and 3rd stories. The strong-column and weak-beam mechanism formed up to the third story, but not in the 4th and 5th stories.



(1) Relation of story-shear force and inter-story deflection (2) Plastic hinges and time damage

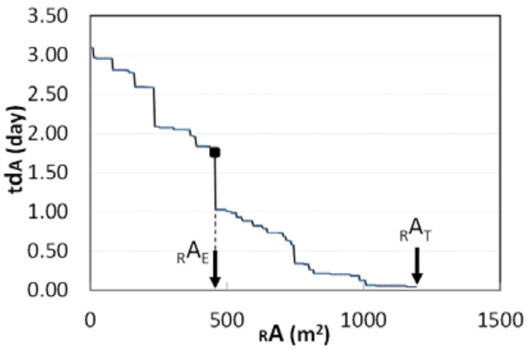
Fig. 7 – Analytical results

The failure mechanism of the column and beam in the frame test in Section 3.2 is flexural failure. Moreover, as shown in Table 3, the ratios of the width to the depth and of the length of the members to the depth are almost the same as the members of the subject building. Therefore, the authors decided to evaluate the time damage of the column and the beam members based on the relation of the time damage and the deflection angle in the structural experiment shown in Fig. 2(2). The time damage corresponding to the deflection angle obtained from the analysis was specifically read from Fig. 2(2).

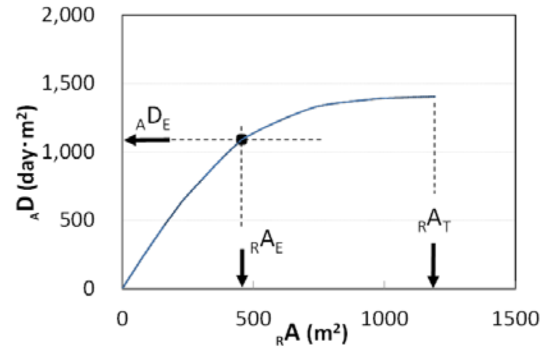
Fig. 7(2) shows the obtained time damage of each member. The time damage is especially large in the beams of the 1st and 2nd stories. Those beams require about 2.5 days for the repair.

5.3 Calculation of IRT

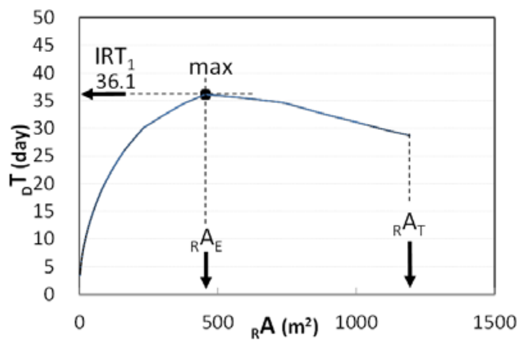
Fig. 8 shows the calculation processes of IRT_1. Figs. 8(1), (2), and (3) correspond to Figs. 4(1), (2), and (3) explained in Chapters 3 and 4. Fig. 8(3) shows that the maximum value of ${}_DT$ is 36.1 days, which means that the IRT_1 determined by the amount and the extent of the damage is 36.1 days.



(1)Relation of ${}_td_A$ and ${}_RA$



(2)Relation of ${}_AD$ and ${}_RA$



(3)Relation of ${}_DT$ and ${}_RA$

Fig. 8 – ${}_td_A$, ${}_AD$ and ${}_DT$ obtained from analysis

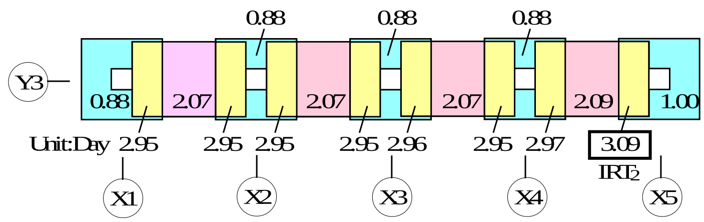


Fig. 9 – ${}_PT$ distribution around Y3 frame of 1st story

Fig. 9 shows the ${}_PT$ distribution around the Y3 frame of the 1st story. ${}_PT$ in the 1st story is larger than those in other stories, and the ${}_PT$ distribution of each frame in the same story is the same. The maximum value of ${}_PT$ occurs in the overlapped repair work area of the X4–X5 beam and the X5 column in Fig.9. The value is 3.09 days. Therefore, IRT_2 determined by the damage concentration is 3.09 days. Note that the values of time damage shown in Fig. 7(2) are not used directly in Fig. 9. Because the repair work of the upper surface of the beam in the nth story is assumed be done on the floor of the n+1th story, and the repair work of the sides and the bottom surface of the beam be done on the floor of the nth story.

From the above, *IRT* is determined by 36.1 days of IRT_1,because $IRT_1$is larger than IRT_2. This is because no large concentration of the damage nor the damage causing the bottleneck occur in this building. Suwa [8] investigated the relationship of damage degree, repair time and total floor area of buildings damaged in the Great Hanshin-Awaji Earthquake (1995). On the basis of the investigation results, the repair time for the subject building is estimated to be about 90 days, which is 2.5 times larger than the calculated value of IRT1. This is mainly because the subject building does not have nonstructural components and the IRT1(36.1days) does not include repair time for them. The authors investigated amount of time damage for buildings with nonstructural components [9]. The results suggest that IRT of buildings with nonstructural components can be about 2 to 4 times larger than that of buildings without nonstructural components. Although further investigation would be required, it could be said that the calculated value of IRT1 is possible.

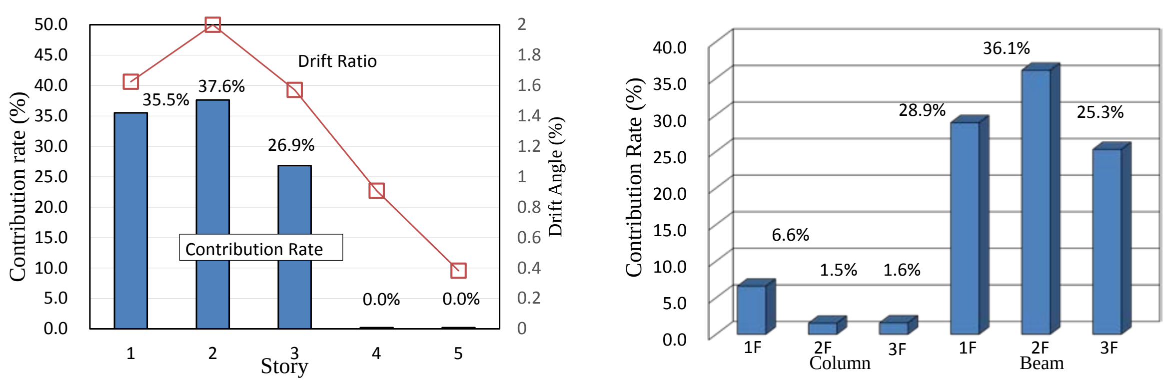
5.4 Influence of damage to each story and members on IRT

The contribution rate of the damage in each story to IRT_1 is shown in Fig. 10(1) by comparison with the drift angle of each story. The contribution rate is a percentage of the IRT_1 generated by the damage to be analyzed in IRT_1 generated by the whole building.

The figure shows that all IRT_1 are produced by the damage in the 1st, 2nd, and 3rd stories. The contribution rate of the 1st and 2nd stories are especially large, which occupies 75% of IRT_1. The reason that the contribution rates of the 4th and 5th storeys are 0 is that the effective repair work areas ${}_{R}A_{E}$ only exist in the 1st, 2nd, and 3rd stories. The reason that the contribution rates of the 4th and 5th storeys are 0 although the time damage of the member in those stories is not 0 is that the damage in those stories is relatively small compared with those of the 1st, 2nd, and 3rd stories. In other words, the repair of the 4th and 5th stories is evaluated to be relatively small and can be completed during the repair work of the 1st, 2nd, and 3rd stories.

This result shows that the damage inhibition in the 4th and 5th stories is not effective, but that of the 1st, 2nd, and 3rd stories is effective in reducing IRT_1. The drift angle of the 4th story is almost 1/100, and the damage considerably occurred. Nevertheless, the contribution rate becomes 0, which is interesting when considering the relation of the repair time and the damage. Therefore, identifying the place where the damage controlling the repair time occurs and its contribution is very important when designing for the purpose of the functional maintenance.

Fig. 10(2) shows the contribution rates of the columns and beams in each story to IRT_1. The contribution rates of the 4th and 5th stories are not shown in this figure because they are 0. The highest contribution rate of the beam is in the 2nd story and produced 36.1% of IRT_1. The 1st and 3rd stories contribute to IRT_1 for 28.9% and 25.3%, respectively. 90% of IRT_1 is produced by the damage to the beams. The highest in the columns is in the 1st story and produced 6.6% of IRT_1.



(1) Contribution rate of damage to each story

(2) Contribution rate of damage to Columns and beams in each story

Fig. 10 – Contribution rate of damage to IRT

6. Conclusion

An index, "Ideal Repair Time (IRT)", to evaluate the severity of earthquake damage from the viewpoint of functional maintenance was proposed, in which severity is defined to be caused by an increase in repair time. The index was formulated taking into consideration the effects of damage state (i.e. amount, extent, and concentration of the damage) on an increase in repair time. The following is a summary of the characteristics of the IRT.

1. Many factors influence the repair time other than the damage state. The IRT is an index that targets only the damage state by eliminating influences by factors other than the damage state.

2. The IRT evaluates the severity of the damage caused by its amount, extent, and concentration. Therefor the influence on the dysfunctional time by each damage in the building can be evaluated, and the damaged areas to be prevented can be identified. The analysis based on the IRT allows structural designers to investigate the validity of the planned collapse mechanism, strength, and stiffness given to the building from the perspective of the functional maintenance.

3. Various types of damage occur in the building, such as the damage to structural components, nonstructural components, and items of equipment. How to express the severity of these damages is different for each. The IRT uniformly evaluates the severity of the different types of damage, and allows a relative comparison of damage-resistant performance of buildings, where different types of damage simultaneously occurred.

4. The IRT is an index that represents the dysfunctional time caused by the damage. From the IRT, ordinary people with no special knowledge on structural engineering can easily understand the relative difference of the damage severity and the damage-resistant performance given to the building. An index that can indicate the necessity of the damage-resistant performance and the secured level of the performance to the owner of the building is significant.

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