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REDEFINED SYSTEM FOR SEISMIC DAMAGE EVALUATION OF REINFORCED CONCRETE BUILDINGS

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Abstract

In a previous study (2012, K. Tajima et al.), a new damage evaluation method, using a damage spectrum representing the relationship between the primary natural period T of a building and the damage index DI of the entire building (2003, Bozorgnia et al.), was proposed. To verify the proposed method, we analyzed the recorded waves and building damage survey results from the earthquake that occurred off the Pacific coast of Tohoku in Japan on March 11, 2011. We found that the proposed method overestimated the state of damage of many reinforced concrete (RC) buildings. Therefore, in order to obtain the difference between the actual horizontal strength of the building and the strength required for design, which is the factor considered here, it was confirmed that by taking into account the strength increase factor Ω (Overstrength Factor) set based on numerical analyses for each RC building, the results of the proposed method corresponded well with the damage status of the building.

This study aims to build a quick and highly accurate system for damage evaluation of these RC buildings. However, the verification results of previous studies are based on parameters individually set for each target building, which vary greatly depending on the performance of each building; it has been pointed out that the parameters applied in these studies have a limited scope of application. Therefore, upon clarifying the issues of damage evaluation based on the current damage spectrum and its application limits, we conducted an analytical study based on frame models and investigation reports of damage sustained from past earthquakes and redefined the rational parameters on a theoretical basis. Specifically, the following parameters were redefined:

1) Restoring force characteristics were modified from bi-linear type to tri-linear type.

2) The hysteric energy absorption E_H evaluation method was revised for the calculation of damage index.

3) Damage categories were newly redefined from those proposed by Park et al., based on damage classification criteria and numerical analysis.

4) The overstrength Factor Ω was redefined as a function corresponding to the natural period of the building, rather than a constant value.

Upon verifying the above correction or redefinition, it was confirmed that the statuses of damage from past earthquakes can be accurately evaluated for buildings by using the improved parameters. Furthermore, an earthquake damage evaluation was conducted on buildings—using the improved damage spectrum with redefined parameters—in the Nankai Trough, where an earthquake is anticipated to occur in the future; the possibility of the earthquake damage being much greater than that caused by large earthquakes in the past was confirmed.

Keywords: Damage Spectrum, Earthquake Damage Evaluation, RC Building, Damage Index

1. Introduction

The method used in Japan to assess damage to reinforced concrete buildings (herein termed, "RC") caused by earthquakes is based on the concept of seismic capacity evaluation. In seismic capacity evaluation, the seismic performance is assessed based on the energy obtained from the strength and toughness of the building under a static external force. It is therefore thought that the effects of seismic motion characteristics are not sufficiently considered in evaluations of seismic damage to RC buildings.

In response to this problem, the authors [1] propose the creation of a rapid and high-accuracy damage evaluation system comprised of three stages. In the first stage, we adopt the damage spectrum proposed by Bozorgnia and Bertero [2], which makes it possible to obtain an approximate value of the extent of damage to a group of RC buildings using seismic motion as an input. However, past methods of evaluation have emphasized on simplicity, and many of the parameters used to create the damage spectrum were simply set on the basis on various assumptions. Hence, problems have been highlighted in the accuracy of damage evaluations.

In this study, we examine the issues and limitations of a method of damage evaluation based on the proposed damage spectrum, and attempt to redefine rational parameters based on a theoretical treatment utilizing past seismic damage survey reports and the results of analysis using frame models. In addition, using an improved damage spectrum that makes use of the redefined parameters, we attempt to estimate seismic damage to RC buildings resulting from the anticipated Nankai Trough earthquake.

2. Issues due to using previous damage spectrum in methods of damage evaluation

The damage spectrum models buildings using a single degree of freedom (referred herein as SDOF) and expresses the relationship between the elastic primary natural period T (sec) and the damage index DI (Figure 1). The damage index shown on the vertical axis evaluates specific damage states by associating these with damage categories. To calculate the damage index DI, the following equation [2] is used.

$$DI_2 = [(1-\alpha_2)(\mu-\mu_e)/(\mu_{mon})] + \alpha_2(E_H/E_{Hmon})^{1/2} \quad (1)$$

Here, μ is the displacement plasticity, μ_e is the ratio of maximum elastic deformation to yield deformation, μ_{mon} is the final plasticity during monotonous horizontal loading, E_H is hysteresis energy absorption during the earthquake, E_{Hmon} is hysteresis energy absorption during monotonous horizontal loading, and α_2 is a constant.

Additionally, in order to create a damage spectrum using the DI_2 equation, it is necessary to set the acceleration response spectrum for use in the design, strength reduction factor R, building restoring force characteristics, ultimate plasticity during horizontal loading μ_{mon}, and the constant α_2.

In a previous study [1], various parameters set for the DI_2 equation were examined, and their validity was confirmed through comparison with the results of damage surveys from the Great East Japan Earthquake.

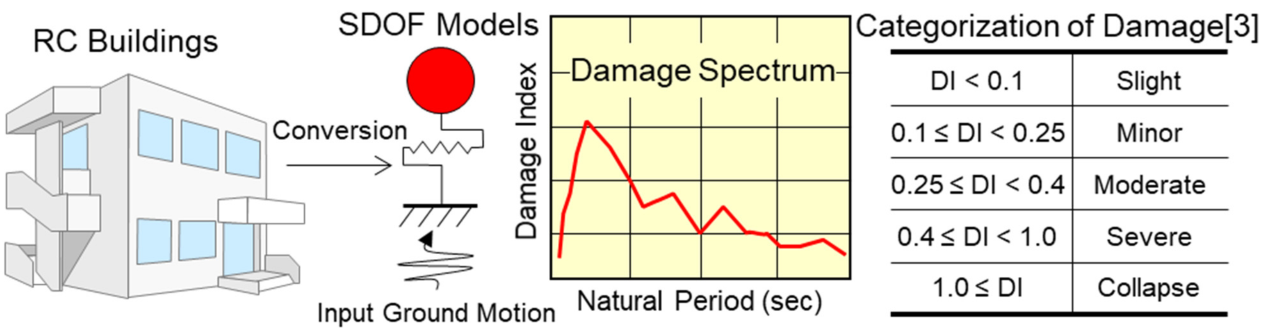


Fig.1 – Outline of damage spectrum

However, subsequent studies have raised the following issues:

(1) Although the buildings' restoring force characteristics has been treated as bi-linear, this may show a tendency that is different from the hysteresis behavior of RC buildings.

(2) The same damage index value may be calculated, despite inconsistencies in hysteresis behavior during an earthquake.

(3) The effects of input seismic motion and the positioning of physical damage is unclear in the relationship between the damage categories and damage index.

(4) The average value obtained from frame analysis results for four buildings was provisionally adopted for the strength increase coefficient Ω. Its applicability to RC buildings is therefore unclear.

3. Re-examining the parameters applied to the damage spectrum

3.1 Restoring force characteristics of RC buildings

To solve issue (1), we have attempted to improve the restoring force characteristics by constructing a frame model for RC buildings and comparing the SDOF model with hysteresis behavior during an earthquake.

According to the ground survey of damage in the 2016 Kumamoto Earthquake, buildings constructed in the 1970s suffered enormous damage. A frame model was therefore constructed based on a fiber model assuming a 4×2 span two-layer frame designed using the general structural design methods of the 1970s. Figure 2 shows the outline of the constructed frame model. The columns and beams were modeled as fiber elements, and joint sub-elements were added to reproduce the pullout behavior of the longitudinal bars. In addition, the beam-column joints and foundation were assumed to be rigid bodies, and the slab was assumed to be rigid. Figure 3 shows the stress-strain relationships for concrete and steel and moment-rotation relationship for joint sub-element used for the fiber analysis. OpenSees [4] was used for the analysis.

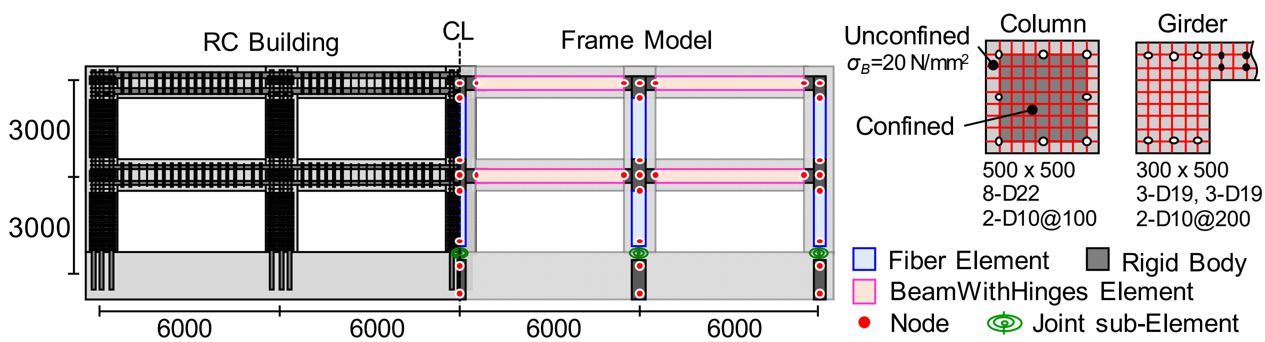


Fig.2 – Outline of the constructed frame model

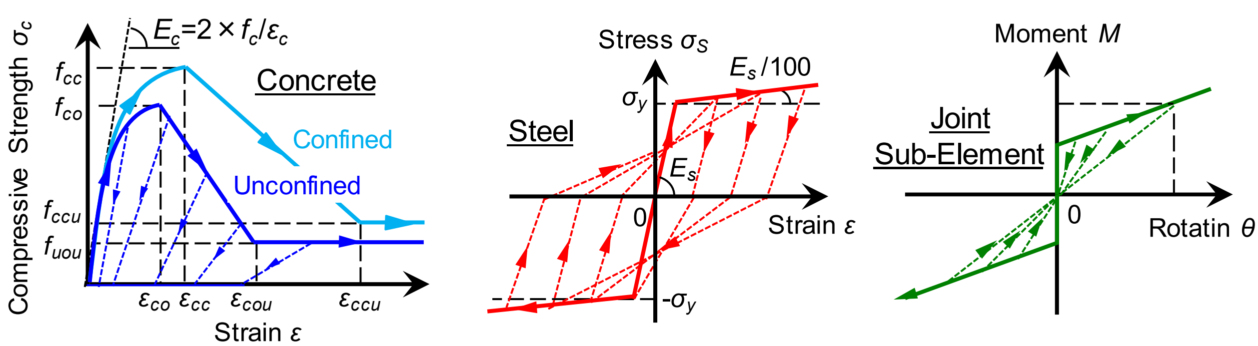
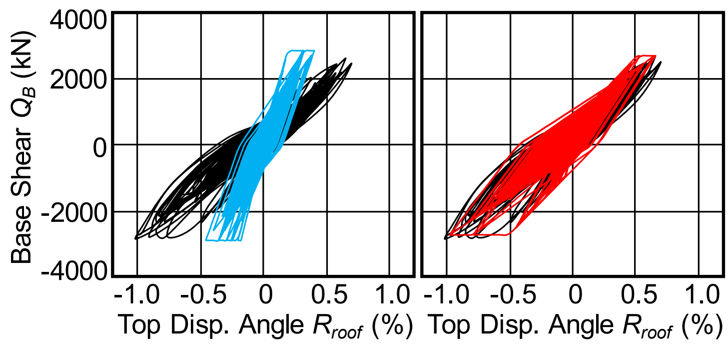


Fig.3 – Stress-strain relationships for material and moment-rotation relationship for joint sub-element

There are two types of restoring force characteristics in SDOF models; a newly set tri-linear type in addition to the bi-linear type that only considers the current yield point. The restoring force characteristics from the modified Clough model are adopted in the tri-linear model, with the first break point being the flexural cracking point of the pillar material, and the second break point being the point at which the column base reinforcement yields.

A seismic response analysis was performed on the frame model and SDOF models using the two types of restoring force characteristics. Damping was considered to be proportional to the tangent stiffness, and the damping constant was set at 3%. BCJ-L2 was used as the input seismic wave, which is a simulated wave from the Building Center of Japan. Figure 4 shows the base shear (Q_B) - top displacement angle (R_{roof}) relationships. While the response of the bi-linear restoring force characteristic is limited to approximately half of the frame analysis result, the tri-linear type restoring force characteristic can be confirmed to have a good response. Furthermore, comparing the damage index calculated from the results of analysis, the results for the tri-linear type show values equivalent to those of the frame analysis. This suggests that the tri-linear type is more appropriate for modeling the restoring force characteristics of the SDOF model.



	DI_2	Frame/SDOF
Frame Model	0.51	-
SDOF Model (bi-linear)	0.70	0.73
SDOF Model (tri-linear)	0.51	1.00

Fig.4 – Base shear (Q_B) - top displacement angle (R_{roof}) relationships

3.2 Damage index by focusing on the hysteretic energy absorption during an earthquake

Utilizing the frame model constructed in section 3.1, we have examined problem (2). First, we conducted a seismic response analysis using a total of 43 seismic motion inputs measured from waves from the Great East Japan Earthquake, Kumamoto Earthquake, and others, and then attempted to understand the effects of differences in input ground motion on changes in the damage index.

Figure 5 shows the relationship between the damage index (DI_2) calculated from the results of the seismic response analysis and the maximum top displacement angle (R_{max}). Qualitatively, the damage index shows a tendency to increase with increase in the maximum response value. However, comparing by each earthquake type, the analysis results of the Great East Japan Earthquake show a large damage index value in the range in which the response is small compared to that of the Kumamoto earthquake and other observed waves. This may be due to the duration of the seismic wave. The Kumamoto earthquake and other observed waves tended to be near-field earthquakes with a relatively short duration. However, since the Great East Japan Earthquake was a long-duration seismic motion, it is inferred that the contribution to the damage index associated with the hysteretic energy absorption during the earthquake had a large effect. We have therefore focused on KMM006NS and MYG004EW for which the calculated damage indices show almost identical values.

Figure 6 shows the base shear (Q_B) - top displacement angle (R_{roof}) relationship in the result from each seismic response analysis. The maximum response value is approximately twice as large for KMM006NS. In addition, MYG004EW traces a path near the maximum response value, and considering the long duration, the increase in the damage index accompanying the hysteretic energy absorption, is considered to be severe. However, KMM006NS draws a large path due to greater input acceleration, but afterwards, the rigidity is reduced and a small path is drawn. The cumulative increase in the damage index accompanying the hysteresis energy absorption is considered small compared to MYG004EW. Here, a difference can be observed when the state of damage to the frame in the analysis results is confirmed. In MYG004EW, a decay mechanism is not formed, while in KMM006NS a decay mechanism is created, and it can be confirmed that the core concrete has reached a compression softening stage. However, after applying the obtained damage index values to the current damage categories, both the damage states are judged to be "serious".

Therefore, to understand the effect of hysteretic energy absorption during earthquakes on damage to RC frames, we have focused on the damage index concept based on Mehanny and Deierlein's [5] energy absorption criterion. We propose a damage index, DI_d, that reduces the weight of damage that is less than the maximum experienced response value compared to the current damage index DI_2. The DI_d expression is shown below:

$$DI_d = [(1-\alpha_2)(\mu-\mu_e)/(\mu_{mon})] + \alpha_2\left[\left(E_{H,PHC}+E_{H,FHC}\right)/\left(E_{Hmon}+E_{H,FHC}\right)\right]^{1/2} \quad (2)$$

Here, $E_{H,PHC}$ is the hysteretic energy absorption during an earthquake corresponding to the main half-cycle, while $E_{H,FHC}$ is the hysteretic energy absorption during the subordinate half cycle (Figure 7).

Figure 8 shows the relationship between the damage index (DI_d) and maximum top displacement angle (R_{max}). It can be observed that DI_d can improve on overestimates in the damage index due to the effect of duration of the input ground motion. Indeed, judging the extent of damage from the obtained DI_d value, in case of MYG004EW, there is moderate damage while for KMM006NS, there is severe damage. It is confirmed that this corresponds well to the physical damage states in the frame model.

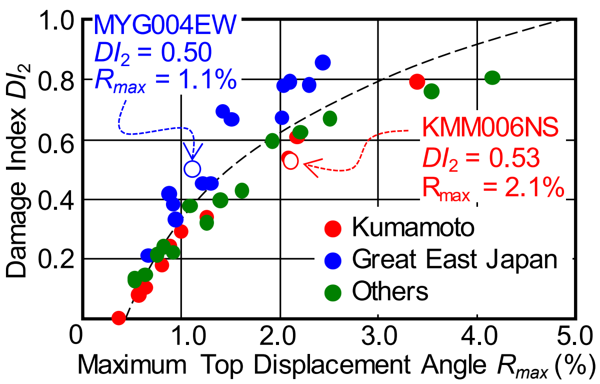


Fig.5 – DI_2 - R_{max} relationship

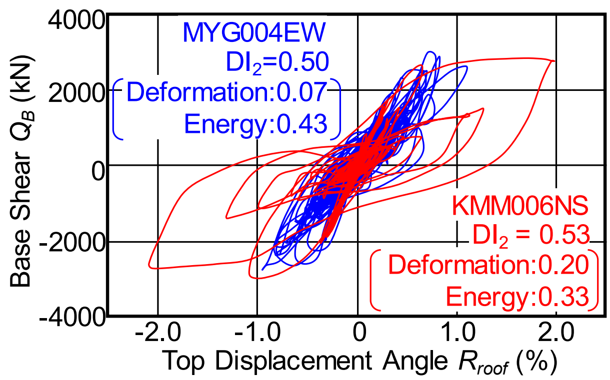


Fig.6 – Q_B - R_{roof} relationship

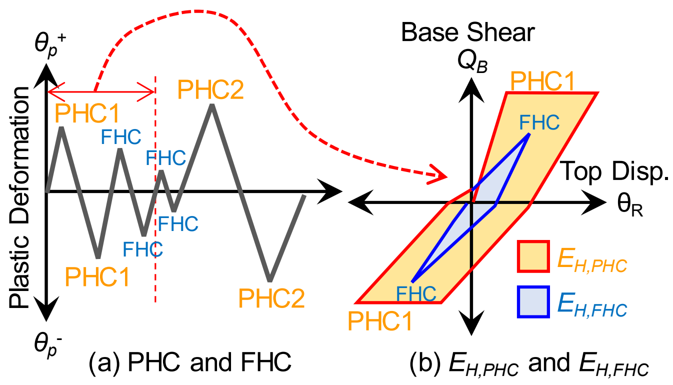


Fig.7 – $E_{H,PHC}$ and $E_{H,FHC}$

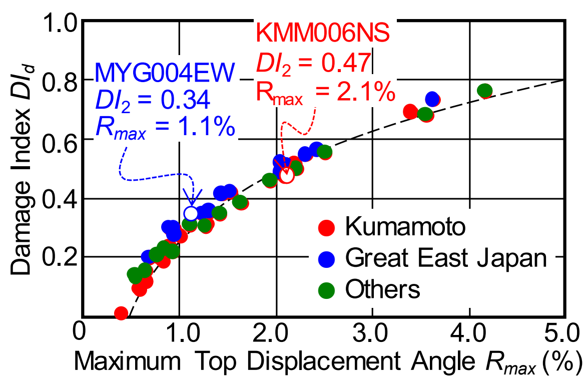


Fig.8 – DI_d - R_{max} relationship

3.3 Damage categories

For examining problem (3), we propose a new damage category for the damage index DI_d proposed in section 3.2. Here, based on analytical evaluation of the frame model, we have attempted to construct a new damage category that links the damage index DI_d and seismic damage to the frame. The frame to be analyzed is a frame with three patterns of collapse based on the 3-layer RC frame in the full-scale destructive test [6] (total collapse, partial collapse (2-layer or single-layer) and the method used to create the frame model based on the fiber model is the same as in Section 3.1.

In the Japanese method of damage evaluation, it is typical to evaluate the critical state or damage level of a building or layer according to the proportion of the extent of damage to its members. Therefore in this study, we define the extent of damage to members as shown in Figure 9 with reference to the Japanese concept of methods of damage evaluation, and the ratio is associated with the damage grade for the whole building. The specific damage states are as follows; Grade I is the "usage limit state / minor damage or less"; Grade II is "repair limit state /little to moderate damage", Grade III is "safety limit state / major damage", and Grade IV is "possibility of collapse".

Figure 10 shows the relationship between the damage grade and damage index DI_d for the seismic response analysis results of each frame model with input seismic motion as parameters. Hence, it is possible to confirm the same tendency in all cases regardless of differences in the type of collapse. Furthermore, the damage index can be separated at the point where the damage grade changes. Therefore, we have defined new damage categories as shown in Table 1.

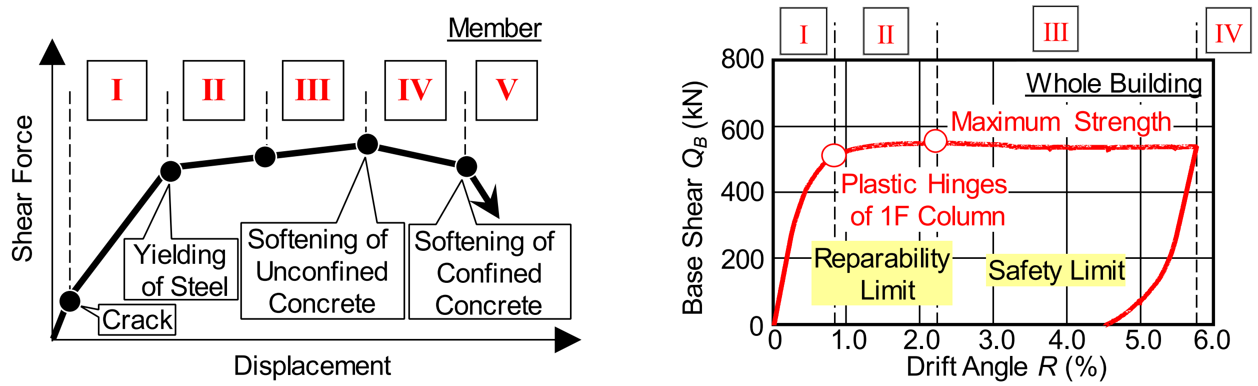


Fig.9 – Damage degree of member and damage category of whole building

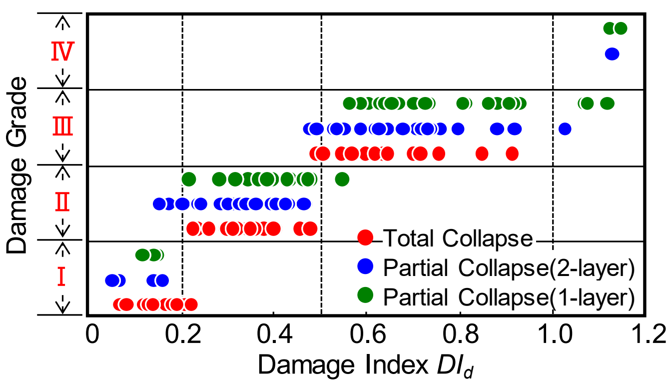


Fig.10 – Damage grade - damage index DI_d relationship

Table 1 – New damage categories for DI_d

Damage Grade	Damage Index DI_d	Damage State and Limit State
I	$DI_d < 0.2$	Slight, Minor Serviceability limit state
II	$0.2 \leq DI_d < 0.5$	Moderate Reparability limit state
III	$0.5 \leq DI_d < 1.0$	Severe Safety limit state
IV	$1.0 \leq DI_d$	Collapse

3.4 Over strength factor Ω

Finally, we examine the over strength factor Ω for the RC building group shown in problem (4). The coefficient Ω is expressed as the ratio between the building strength assumed in the design and actual strength. The current method uses Ω_{Ave} = 4.5 as the average value of results obtained using the trial and error method against the extent of damage suffered by 4 RC buildings damaged in the Great East Japan Earthquake. However, as the coefficient Ω is calculated individually for each RC building, it is difficult to set an accurate coefficient Ω for a group of RC buildings in an area.

We have therefore attempted to estimate the coefficient Ω for a group of RC buildings by referring to a damage survey report [7] from the Hyogoken-Nanbu earthquake. The target RC buildings are classified into general and piloti-type buildings that have been designed since the establishment of new seismic standards, from which a total 1673 general buildings were extracted. Confirming the trends in building damage, damage was limited to minor damage or less in 80 - 100% of the buildings, regardless of building height. It can therefore be inferred that buildings designed according to the new seismic standards have incurred less damage at a minimum coefficient Ω_{min} Therefore, in this study, the coefficient Ω is calculated for the observed waves in the Hyogoken-Nanbu earthquake (JMA Kobe) such that the damage index DI_d falls below 0.2, which corresponds to the upper limit for minor damage. It should be noted that the coefficient Ω calculated in this study does not correspond to the maximum strength of a building. The range of damage index DI_d corresponding to minor damage or less (Grade I) is 0 - 0.2, and it is quite possible for individual RC buildings to have $DI_d < 0.2$. The coefficient Ω calculated here is therefore considered to correspond to its minimum value Ω_{min}, which is considered to be the minimum limit for the target RC buildings. It may be noted that in the damage assessment method using the damage spectrum, the seismic response analysis is conducted at the current point in time and implemented by using an SDOF model that uses observed waves. Hence, the effective input to buildings is not appropriately assessed, since consideration is not made of the effects of distance attenuation of seismic motion etc. Therefore, because these effects are included in the Ω_{min} obtained here, it is inferred that an overestimated value is obtained. Improvements are required with regards to this issue, and are a prospective topic for future research.

Here, an arbitrary coefficient Ω was set to create a restoring force characteristic corresponding to an elastic primary natural period T_0 = 0.1 - 1.0 s (ΔT_0 = 0.02 s), and a seismic response analysis was conducted using JMA Kobe as the input seismic motion. The damping was considered to be proportional to the tangent stiffness, and the damping constant was set to 3%. Subsequently, Ω was reset until the calculated damage index DI_d was close to 0.2, and seismic response analysis was repeated to ultimately calculate Ω_{min}. Furthermore, in the current design standards, the structural characteristic coefficient Ds was set according to the collapse pattern of the frame. Ds was therefore varied in the range 0.30 - 0.45 (ΔDs = 0.05) for the RC buildings. It may be noted that in the current method of damage assessment using the damage spectrum, the final plasticity μ_{mon} is simply assumed to be 12 for the tough fracture type and 6 for brittle fracture type. In this study, for evaluating Ds, the following equation is used.

$$D_s = 1/(2\mu_{mon} - 1)^{1/2} \tag{3}$$

Figure 11(a) shows the Ω_{min} - T_0 relationship, compiled for each structural characteristic coefficient Ds. When T_0 is between 0.1 - 0.3 sec, the coefficient Ω_{min} attains a maximum value. When T_0 is between 0.3 - 0.7 s, Ω_{min} decreases linearly along with an increase in the elastic primary natural period. Furthermore, when T_0 is in the range 0.7 - 1.0 sec, the trend of decrease of Ω_{min} diminishes, converging close to 1.0. Ω_{min} is calculated using the following equations according to the period band as shown below.

$$\Omega_{min} = \Omega_{top} \quad (T_0 \leq 0.3 \text{ sec}) \tag{4-1}$$

$$\Omega_{min} = \alpha \cdot T_0 + \beta \quad (0.3 < T_0 \leq 0.7 \text{ sec}) \tag{4-2}$$

$$\Omega_{min} = 1.0 \quad (0.7 \text{ sec} < T_0) \tag{4-3}$$

$$\alpha = -2.5\Omega_{top} + 2.5 \tag{4-4}$$

$$\beta = 1.75\Omega_{top} - 0.75 \quad (4\text{-}5)$$

Here, Figure 11(b) shows the results of estimation of Ω_{min}. Although the estimated results do not consider the variations in the range where T_0 is between 0.1 - 0.3 sec, the overall trend of Ω_{min} is well expressed. Figure 12 shows the damage spectrum for the Hyogoken-Nanbu earthquake. When Ω = 1.0, DI_d exceeds the minor damage range for the case where T_0 is less than 0.6 sec. However, when Ω_{min} is calculated using the proposed formula, the damage index DI_d is approximately 0.2 or less, and the expected result is obtained.

4. Estimating seismic damage using the damage spectrum by applying the re-examined parameters

Using a disaster spectrum with the parameters that were already re-examined, we attempted to estimate earthquake damage in a real area using a hypothetical seismic wave of the Nankai Trough earthquake presented in the Central Disaster Prevention Council documents [8].

As the seismic motion presented is an acceleration waveform of engineering bedrock (Vs = 350~700 m/s in the corresponding layer), this was converted into a surface ground motion acceleration waveform using equivalent linear analysis based on 1-dimensional multiple reflection theory. The building database was set based on field surveys and map data. The elastic primary natural period of RC buildings was calculated from the relationship with the building height, based on the measured data of 69 concrete buildings by Arakawa et al. [9]. The building height was obtained by multiplying the number of floors by the equivalent story height h = 3.5 (m), which was the average value obtained from the statistical analysis of approximately 1.35 million buildings measured using aerial laser measurement by Ashie et al. [10].

Figure 13 shows the damage index distribution and damage grade distribution created by the damage spectrum using parameters before and after re-examination. However, as the seismic standards for each building in the area are unknown, here we assume that all buildings adhere to the new seismic standards. While using the unrevised parameters, the range in which the damage index increased overall, was conspicuous, and "Grade III" accounted for the majority of damage categories. However, when the revised parameters were used, the damage index was generally less than 0.4, and "Grade II" accounted for the majority of damage categories. The reason for this difference in damage assumptions is considered to be due to the unrevised parameters being focused on buildings with comparatively severe damage while the revised parameters are instead based on the statistical distribution of damage to buildings. Furthermore, considering typical damage during the recent large earthquakes, it can be inferred that relatively minor damage to buildings adhering to the new seismic standards better captures the earthquake damage trends. However, considering that even as per the new seismic standards, most buildings show Grade II damage (corresponding to moderate damage), there is concern that these may be more seriously damaged in the hypothesized Nankai Trough earthquake than in large earthquakes in the past.

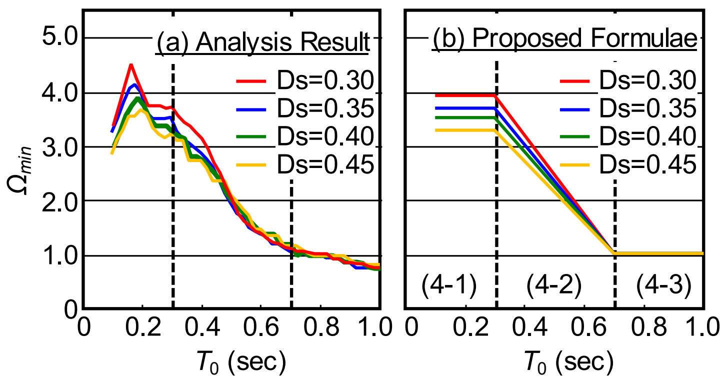


Fig.11– Ω_{min} - T_0 relationship

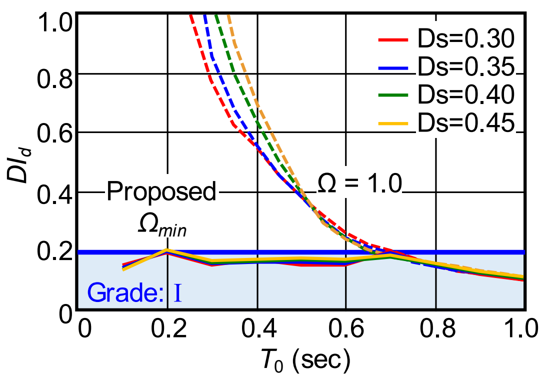


Fig.12 – DI_d - T_0 relationship

Fig.13 – Estimated seismic damage using the damage spectrum

5. Conclusions

Focusing on 4 issues using the method of seismic damage assessment based on a proposed damage spectrum, we have re-examined the parameters to be applied. In addition, based on these revised parameters, we have attempted to estimate earthquake damage to RC buildings in the anticipated Nankai Trough earthquake. The following findings are obtained.

(1) As a restoring force characteristic applied to the SDOF model for RC buildings, the tri-linear model is more appropriate than the bi-linear model which has thus far been used for the sake of simplicity.

(2) Focusing of Mehanny and Deierlein's [5] concept of a damage index based on energy absorption, we have proposed a new damage index DI_d. As a result, it is possible to improve upon overestimation of the damage index due to the effects of duration of input seismic motion, and the state of frame damage can be evaluated appropriately.

(3) Through frame analysis, damage categories for the newly proposed damage index DI_d have been obtained by associating member damage with frame damage.

(4) A method is established to calculate Ω_{min}, corresponding to the lower limit of the strength increase coefficient, by linking it to the primary natural period and structural characteristic coefficient of the building. It will however be necessary in the future to re-examine this after having appropriately evaluated effective input to buildings.

(5) Using a damage spectrum with the revised parameters, we have attempted to estimate the damage to RC buildings in a Nankai Trough earthquake scenario. As a result, it is understood that there is the possibility of moderate damage even with the new seismic standards.

6. References

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