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BASIC STUDY ON SPEEDILY AND APPROPRIATELY EVALUATION METHOD OF BUILDING DAMAGE STATES USING CAPACITY CURVE

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Abstract

In Japan today, after an earthquake occurs, building damage is evaluated by engineers in accordance with a particular emergency safety evaluation method. After a large earthquake, many engineers are required to perform such evaluations on site, which becomes a hindrance to early recovery. In addition, since human judgment is subjective and each engineer has a heavy workload, variations in evaluation accuracy may occur. This study thus aims to propose a method for speedily and appropriately evaluating the damage state of damaged buildings.

In order to establish this evaluation method, it is necessary to construct a model that can reproduce the damage states of actual buildings, and also create a method for assessing the damage state at structural member levels. Thus, we first express the capacity curve used in this study in terms of base shear versus top deformation, and construct an analytical model capable of reproducing the base shear–top deformation relationship obtained by experiment in a full scale, five-level reinforced concrete frame specimen. Then, by using information on the crack width and reinforcement yield state of each structural member (column, beam, and attached wall), the damage level of structural members is assessed. After the above, a correlation is clarified between the global damage state that is found by the local damage state for structural members and the capacity curve. To be specific, the following five damage limit state points are identified on the capacity curve, obtained by frame analysis: the point where a structural member yields first; the point where the whole frame reaches its elastic limit; the point where the whole frame becomes plastic and the strength near the maximum yield strength is reached; the point where horizontal yield strength decreases slowly; and the point where horizontal yield strength decreases remarkably and vertical yield strength is partially lost. These five identified states and the maximum response of building due to an earthquake are used to speedily determine the state of building damage. The evaluation method proposed above is applied to actual reinforced concrete buildings damaged by the Tohoku Region Pacific Coast Earthquake, and its applicability is discussed.

Keywords: Local damage state for structural component, Global damage state, Capacity curve, Damage limit state points

1. Introduction

Currently, emergency risk discriminators assess building damage situations after earthquakes in Japan. Many discriminators and a long period of time are necessary for assessment when a large earthquake occurs. Residents stay at evacuation shelters and companies stop businesses during the assessment period; thus, methods to speedily and appropriately assess damage are necessary. There has been a wide variety of research on this subject [1-4]. A practical assessment method must be rational and minimize the number of measurement points. Therefore, for the early recovery of buildings after an earthquake, proposals for quick, appropriate, and rational methods to assess member and building damage are necessary. One possible approach is to accurately assess the damage of actual members and buildings and then clarify the relationship between building damage state and structural characteristics.

Taking this approach, this investigation considers full scale, five-level reinforced concrete frame specimens [5,6]. The damage condition of the members was assessed using experimental data, and methods to evaluate the building damage situation were investigated. Namely, the residual seismic capacity ratio was calculated based on damage category evaluation standards [7], and the validity of the results was investigated. The displacement damage category was plotted on base shear-top deformation plots obtained from experiments on full scale, five-level reinforced concrete frame specimens. The reasonableness of the relationship was clarified using crack and rebar yield information.

2. Past global damage state of full scale five-level reinforced concrete frame specimens

2.1 Overview of specimens

The 2014 and 2015 full scale five-level reinforced concrete frame specimens have two spans and one span, and long and short directions, respectively. The wall categories for each specimen are shown in Fig. 1. The 2014 specimen used wing walls as the structure, while the 2015 specimen used wing, spandrel, and hanging walls.

2.2 Shear force-deformation relation obtained experimentally

Static loading experiments were conducted on the 2014 and 2015 full scale five-level reinforced concrete frame specimens [5,6]. Actuators for excitation were installed on both the roof and fourth level, and repetitive positive loading was conducted. Figures 2 and 3 illustrate the experimental shear force-representative deformation relation under both positive load and the peak point for each load.

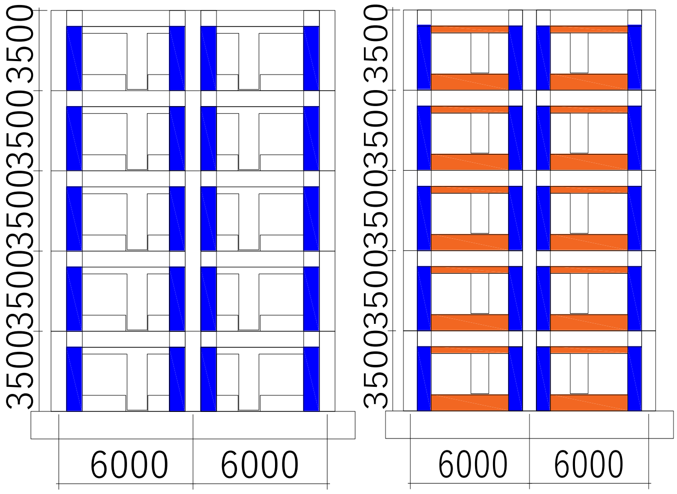


Fig.1 The attached wall categories
(left : 2014 specimen, right : 2015 specimen)

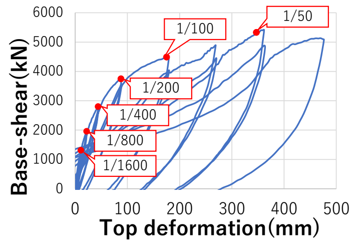


Fig.2 base shear–top deformation relationship (2014 specimen)

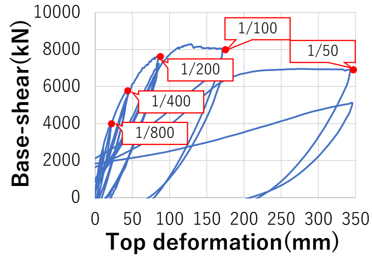


Fig.3 base shear–top deformation relationship (2015 specimen)

2.3 Damage category evaluation results

Previous studies [5,6] have evaluated the damage category for each member and building level of each specimen using the damage category evaluation standards [7]. Figures 4–6 illustrate the damage category when the displacements of the level with the most severe damage category was used for assessment. Figures 4 and 5 did not consider attached walls, and both 2014 and 2015 specimens were assessed as "severely damaged" at about 1/200 load. However, the base shear-top deformation curve did not yield at 1/200 load; thus, the "severe damage" assessment is excessively on the safe side. Figures 7–11 show the cracking and rebar yield positions when the 2014 specimen was under 1/800 load, 1/400 load, 1/200 load, 1/100 load, and 1/50 load, respectively. Similarly, Figs. 12–15 show similar data for the 2015 specimen except for 1/50 load (only rebar yield information is shown for 1/800 load). The cracking information is obtained from previous studies [8,9]. The black dots in the figures show the rebar yield position of columns and beams, and the red dots indicate the rebar yield position of the attached walls. The yield assessment of rebars was only considered at the locations where strain gauges were attached in previous studies. The details of each damage category in the evaluation standards [7] are shown in Table 1. There was no rebar exposure, buckling, nor any large shear cracks in the damage diagram after 1/200 load on the 2014 specimen (Fig. 9). Similarly, there were no large shear cracks in the damage diagram after 1/200 load on the 2015 specimen (Fig. 14). Therefore, the "severely damaged" assessment was excessively on the safe side based on both the base shear-top deformation curve and damage diagram. Previous studies [5,6] have reported similar conclusions. When the seismic performance was evaluated after ignoring the attached walls of the 2015 specimen, the assessment was dangerous compared to when the attached walls were included (Fig. 6). However, the assessment was "severe damage" at 1/200 load to 1/100 load where the base shear-top deformation curve yielded. Again, the assessment was excessively on the safe side based on both the base shear-top deformation curve and damage diagram.

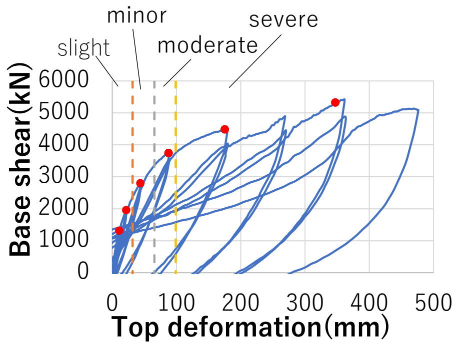


Fig.4 past global damage state（2014）

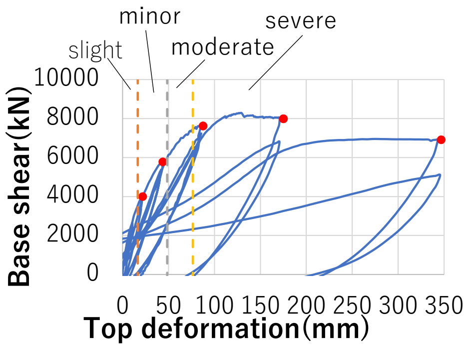


Fig.5 past global damage state (2015, wall)

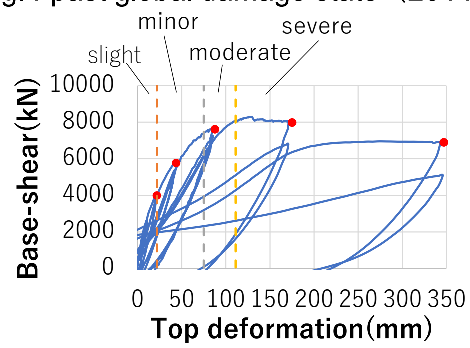


Fig.6 past global damage state (2015, no wall)

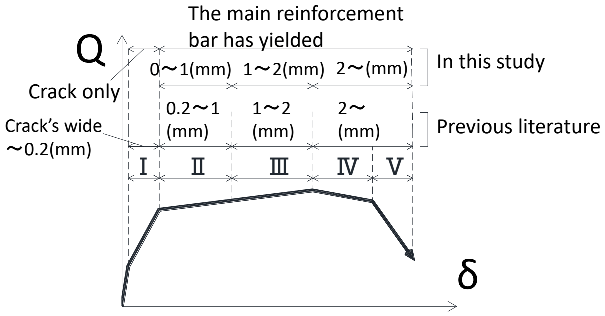


Fig.16 local damage state

Table.1 global damage state

slight	Minor or almost no damage on columns, bearing walls, and secondary walls
minor	Typical shear cracks and bending cracks in columns, shear cracks in load-bearing walls, and significant damage to RC secondary walls and non-structures
moderate	Typical shear cracks and bending cracks in columns, shear cracks in load-bearing walls, and significant damage to RC secondary walls and non-structures
severe	Reinforcing bars are exposed and buckled due to shear cracks and bending cracks in columns, causing large shear cracks in load-bearing walls and significantly lowering proof stress
collapse	Columns and bearing walls were severely destroyed, and the entire building or a part of the building collapsed

Table.2 local damage state in this study

Local damage state I	Cracks have occurred and the main reinforcement bar has not yielded
Local damage state II	The main reinforcement bar has yielded and cracks with a width of 1 mm or less have occurred
Local damage state III	The main reinforcement bar has yielded and cracks with a width of 1 to 2 mm have occurred
Local damage state IV	The main reinforcement bar has yielded and cracks with a width of 2 mm or more have occurred.
Local damage state V	The main reinforcement bar buckled, inside concrete collapsed

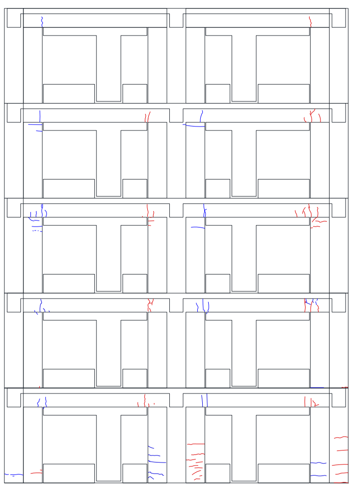


Fig.7 damage diagram at 1/800 (2014,quote from [8])

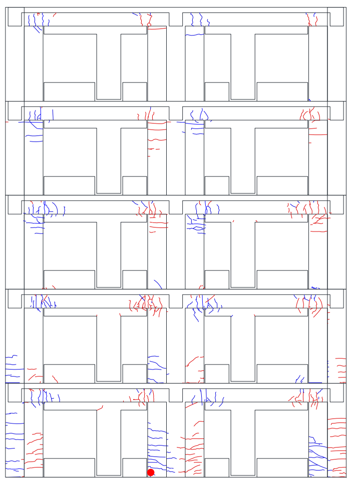


Fig.8 damage diagram at 1/400 (2014,quote from [8])

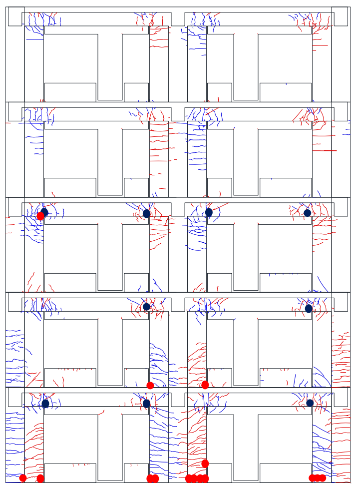


Fig.9 damage diagram at 1/200 (2014,quote from [8])

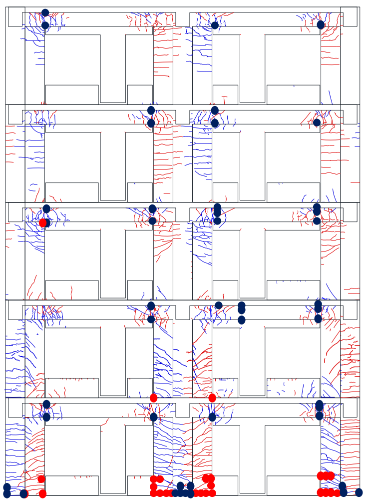


Fig.10 damage diagram at 1/100 (2014,quote from [8])

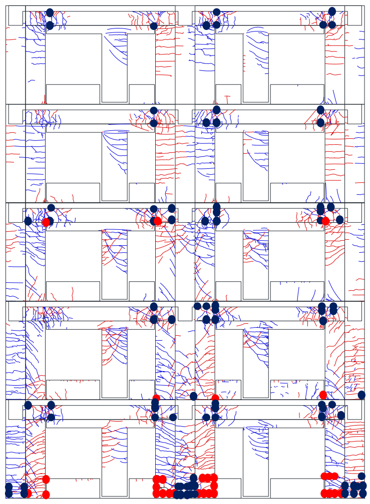


Fig.11 damage diagram at 1/50 (2014,quote from [8])

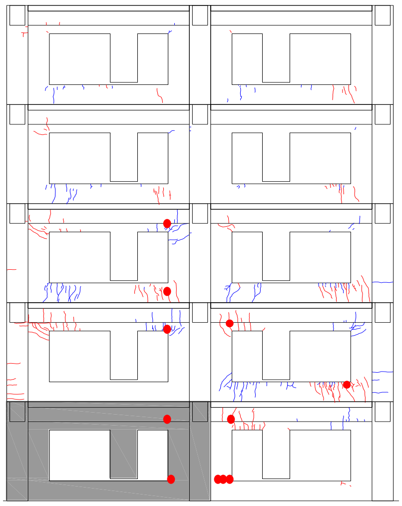


Fig.12 damage diagram at 1/800 (2015,quote from [9])

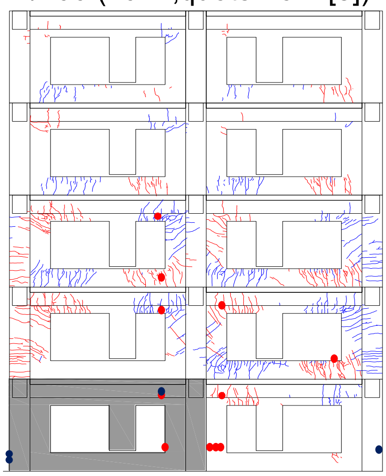


Fig.13 damage diagram at 1/400 (2015,quote from [9])

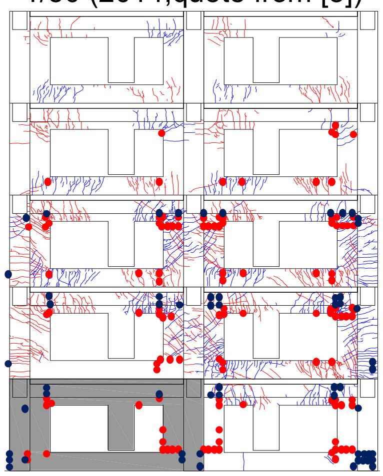


Fig.14 damage diagram at 1/200 (2015,quote from [9])

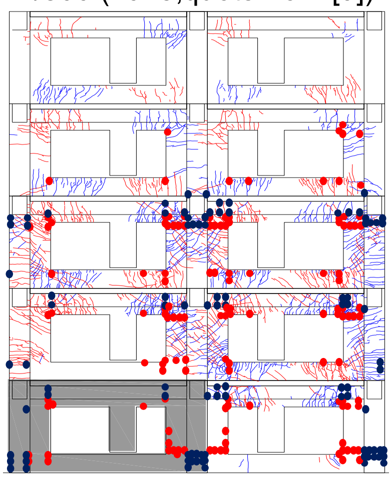


Fig.15 damage diagram at 1/100 (2015,quote from [9])

3. Effect on member damage assessment on the residual seismic capacity ratio

3.1 Member damage assessment

The member damage criteria for assessment in this study is shown in Table 2. Figure 16 displays the relationship between the skeleton curve of the bending members and the member damage category. First, Damage Category I is distinguished from Damage Category II based on whether the rebar yielded. Damage Categories II-IV are then distinguished by crack width. Damage categories were obtained for 1/1600 load, 1/800 load, 1/400 load, 1/200 load, and 1/100 load for the 2014 specimen and 1/800 load, 1/400 load, 1/200 load, and 1/100 load for the 2015 specimen. The columns, wing walls, and beams were assessed for the 2014 specimen, and columns, wing walls, beams, spandrel walls, and hanging walls were evaluated for the 2015 specimen.

Tables 3–6 summarize the member damage by load by specimen. Comparing Figs. 10 and 15, the wing wall damage under 1/100 load was worse in the 2015 specimen in the second and third levels. Similar results were obtained for other loads and levels. For the 2014 specimen, the damage to columns, wing walls, and beams were nearly the same except for columns and wing walls on the first level. In contrast, for the 2015 specimen, damage concentrated on the columns, wing walls, beams, spandrel walls, and hanging walls of the first through third levels; hence, the first to third levels failed. Comparisons between Tables 3 and 5 and Tables 4 and 6 provide roughly the same results.

3.2 Calculation of the residual seismic capacity ratio based on the proposed member damage categories

The residual seismic capacity ratio was calculated according to the damage category evaluation standards [7] using the member damage in Tables 3–6. The damage to all members on all levels in each specimen were simultaneously considered in one method, while damage to members on each level were considered separately in another. The beam seismic performance reduction factors were set to values similar to those of the bending columns. The calculated results are shown in Figs. 17–20.

3.2.1 Comparison of residual seismic capacity ratio when members in each level was considered

The residual seismic capacity ratio in this investigation, when the damage category for members in each

Table.3 damage state of columns and wing walls(2014 specimen,○ : wing walls ,□ : columns)

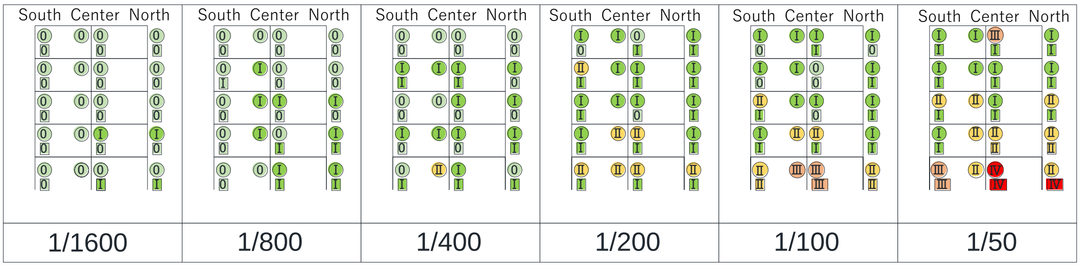


Table.4 damage state of beams(2014 specimen,◇ : beams)

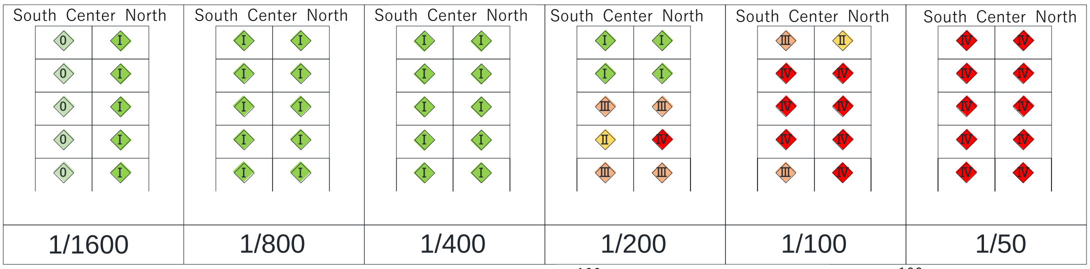


Table.5 damage state of columns and wing walls(2015 specimen,○ : wing walls ,□ : columns)

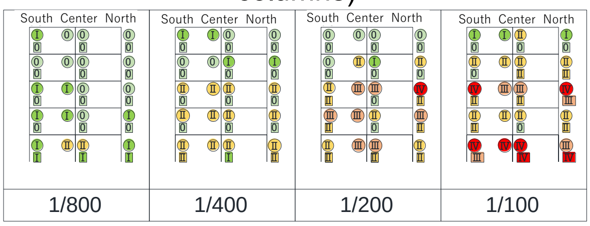
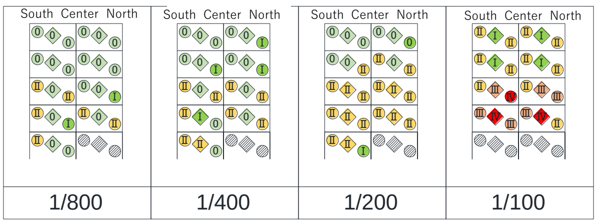


Table.6 damage state of spandrel and hanging walls.(2015,◇ : beams,○ : spandrel and hanging walls , ◈ : no data)



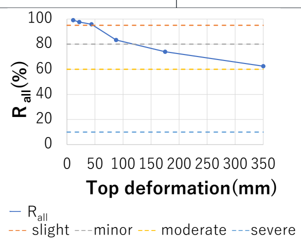


Fig.17 R(%) (2014 , all levels)

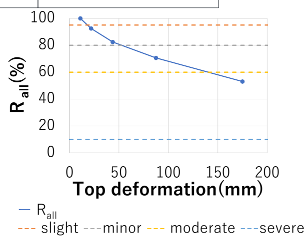


Fig.18 R(%) (2015, all levels)

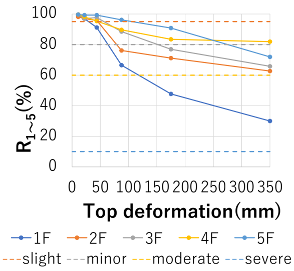


Fig.19 R(%) (2014,each levels)

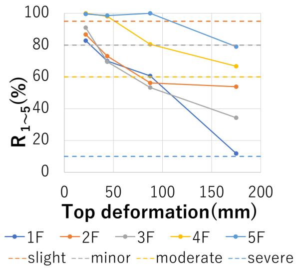


Fig.20 R(%) (2015,each levels)

level was considered, was compared to that of previous studies [5,6]. The residual seismic capacity ratio in this research was divided by that in previous studies [5,6] to obtain a relative proportion against them. A proportion closer to 1 indicates that the result is nearly the same as the literature, and a proportion larger or smaller than 1 shows that the residual seismic capacity ratio is higher or lower (assessment towards the dangerous and safe side) compared to the literature, respectively. The residual seismic capacity ratio proportion when 1/1600 load to 1/400 load was applied to the 2014 specimen was about 1.0 to 1.1 and, on average, approximately 1.0. Therefore, the results in this investigation matched those of the references. In contrast, when the load was 1/200, the proportion was about 1.4 for the third level, and the average over all levels was approximately 1.1. For 1/100 load, the proportions of the fifth, fourth, third, second, and first levels were approximately 1.4, 3.8, 2.3, 2.4, and 1.1, respectively; thus, the average was approximately 2.2. The corresponding values under 1/50 load were approximately 1.6, 8.2, 3.0, 2.7, and 1.4 for the fifth, fourth, third, second, and first levels, respectively; hence, the average was approximately 3.4. When the load was between 1/200 and 1/50, the damage of the wing walls in this research was set to Category I when considering the nonexistent rebar yield in the wall, which led to the difference from previous studies. The residual seismic capacity ratio proportion when attached walls were considered in the 2015 specimen was about 0.9–1.2 when the value was between 1/800 load and 1/200 load. The average was approximately 1.0; thus, similar values were obtained. For 1/100 load, the proportions in the fifth, fourth, third, second, and first levels were approximately 1.0, 1.0, 5.7, 9.0, and 12; hence, the average was approximately 5.7.

3.3.2 Comparison of damage category between when all and each level was considered

The damage category in Figs. 17–20 was applied to Figs. 2 and 3 in Section 2.2. Among the two damage category assessment methods, where one considers all levels simultaneously and the other considers each level independently, the relative appropriateness of the methods was investigated based on the experimental crack and rebar yield situation. The damage category when each level was considered separately was for the level with the smallest residual seismic capacity ratio. When each level was considered separately for the 2014 specimen, the damage category transitioned from “slight” to “minor” immediately after 1/800 load, to “moderate” between 1/800 load and 1/400 load, and to “severe” between 1/200 load and 1/100 load. In contrast, when all levels are considered simultaneously, the damage category transitioned from “slight” to “minor” immediately after 1/400 load and to “moderate” between 1/200 load and 1/100 load. When each level was considered separately in the 2015 specimen, the damage category transitioned from “minor” to “moderate” immediately after 1/800 load and to “severe” immediately before 1/200 load. In contrast, when all levels are considered, the damage category transitioned from “slight” to “minor” immediately before 1/800 load, to “moderate” immediately after 1/400 load, and to “severe” between 1/200 and 1/100 load.

The building damage under each load was evaluated based on member damage from experimental data and compared with the aforementioned damage categories. In the 2014 specimen, rebar yield was not discovered at 1/800 load, one rebar yielded at 1/400 load, the main rebars of beams of the first to third levels yielded and cracking (mostly at wing walls) at 1/200 load, main rebars of beams in all levels and column main rebars, vertical rebars of wing walls, and edge rebars of the first level yielded and shear cracks formed in wing walls at 1/100 load, and main rebars of beams in all levels and column main rebars, vertical rebars of wing walls, and edge rebars of except for the south column and wing walls of the first and second levels yielded and shear cracks formed in wing walls and columns at 1/50 load. Therefore, the appropriate damage category is “slight” up to 1/400 load because there was almost no damage, “minor” for 1/200 load to 1/100 load since there were shear cracks on wing walls, and “moderate” up to 1/50 load because no column rebars buckled nor were exposed. As a result, the damage category when all levels were considered simultaneously was more appropriate for the 2014 specimen.

In the 2015 specimen, the vertical and edge rebars of the attached walls of the first to third levels yielded, and shear cracks were found in the spandrel and hanging walls at 1/800 load. Beams and columns of the first and second levels yielded, and shear cracks were found in spandrel and hanging walls at 1/400 load. The main rebars of north and south columns and vertical and edge rebars of attached walls yielded, and shear cracks were found in columns at 1/200 load. The main rebars of columns and beams in the first to fourth levels and vertical and edge rebars of attached walls yielded, and shear cracks were found in columns at 1/100 load. Therefore, the appropriate damage category is “minor” for 1/800 load to 1/400 load because there were shear cracks on wing walls and “moderate” for 1/200 load to 1/100 load as there were shear cracks in columns; however, the rebars of columns did not buckle, nor were they exposed. As a consequence, the damage category when all levels were considered was also more appropriate for the 2015 specimen.

Calculating the residual seismic capacity ratio for each level and using the ratio of the safest side level for damage categorization results in an evaluation that is excessively safe. Using the residual seismic capacity ratio for all levels simultaneously evened out differences in damage between levels and provided an evaluation that better reflected the actual damage.

3.3.3 Relation between structure curve and damage category

To establish a method to quickly assess the seismic performance of a post-earthquake building, we propose an index that evaluates the damage of a building from the base shear-top deformation relation. A base shear-top deformation relation that considers decreases in proof stress in members is shown in Fig. 23. The evaluation of building damage in the figure is given in Table 7. The capacity curve of the frame that considers decreases in proof stress is discussed below. The section up to (1) in Fig. 23 is elastic, and it is before the first rebar yield. (1) to (2) is also elastic and is before the entire frame becomes plastic. The entire frame is plastic and close to the maximum proof stress in (2) to (3), the framework reaches the maximum proof stress and the horizontal proof stress is decreasing in (3) to (4), and the horizontal proof stress of the framework has significantly decreased and the vertical proof stress is partially lost in (4) to (5).

Defining the boundary points (4) and (5) is extremely difficult because past experiments did not load up to between (4) and (5). In contrast, the validities of boundary points (1) to (3) are investigated in this study by comparing how the boundary points are defined, the actual damage in experiments, and the determined damage category.

Figures 21 and 22 show where the rebars of structural members yielded in each specimen. The yield position and damage category of structural are compared. Wall rebars typically yielded near the boundary

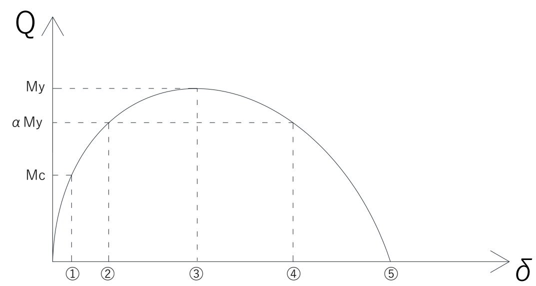


Fig.23 base shear-top deformation relation that considers decreases in proof stress in members

Table.7 the evaluation of building damage in the figure

~① : elastic	the first rebar yield
①~② : elastic~0.8My	the frame's elastic limit
②~③ : 0.8My～My	The entire frame is plastic and close to the maximum proof stress
③~④ : My～0.8My	The frame reaches the maximum proof stress and the horizontal proof stress is decreasing
④~⑤ : 0.8My～0	The frame has significantly decreased and the vertical proof stress is partially lost

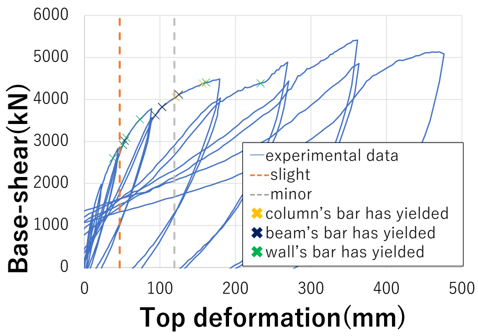


Fig.21 global damage state(2014, all levels)

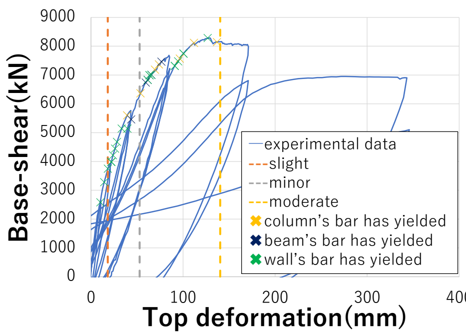


Fig.22 global damage state(2015, all levels) between the “slight” and “minor” categories, and the boundary between “minor” and “moderate” categories was at where the main column rebars initially yielded. The boundary between “moderate” and “severe” categories existed only for the 2015 specimen. This was observed immediately after the maximum proof stress of the experimental base shear-top deformation relation was reached, and all rebars of the observed structural members yielded. Therefore, the structural property curve and the damage category is related. Boundary (1) is defined as where the wall rebars begin to yield (near the boundary between the “slight” and “minor” categories), Boundary (2) is where the first main column rebars begin to yield (near the boundary between “minor” and “moderate” categories), and Boundary (3) is where the rebars of all observed structural members have yielded (near the boundary between the “moderate” and “severe” categories). The validity of these boundaries needs to be confirmed using a comparison of actual damage in real buildings with other structure types.

4. Conclusion

The following insights have been observed from the investigations.

- The residual seismic capacity ratio was calculated with member damage categories obtained in this study. The damage categories of the 2014 specimen were more toward the dangerous side in this research because the damage of wing walls was kept at Damage Category I by considering the wall rebar yield between 1/200 load and 1/50 load, demonstrating the effect of changes in the assessment method.

- The residual seismic capacity ratio was calculated using the damage category evaluation standards [7]. Either each level was individually considered, or all levels were considered simultaneously. Damage categorization was then conducted using displacements. Compared to the experimental results, building damage was evaluated on the safe side when each level was individually examined, and an overall match with actual damage was found when all levels were considered simultaneously. The residual seismic capacity ratio increased in the latter case because the damage in the severe levels was evened out. The damage category boundaries of each level were, in general, on the safe side compared to those of previous studies [5,6]. Therefore, damage category evaluation should be conducted by considering all levels simultaneously to obtain an assessment that more accurately reflects the actual damage.

- If the building damage evaluation method is accurate, then the reasonableness of assessing the building damage based on the base shear-top deformation relation, which is a structural characteristic curve, is demonstrated. Trends in the boundary points for the 2014 and 2015 full scale five-level reinforced concrete frame specimens were found based on rebar yield in structural members. A future research task is to validate the prediction accuracy of building damage using structural characteristic curves of real buildings with different structure types.

5. References

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