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A STUDY ON DAMAGE INVESTIGATION OF DAMEGED BUILDING DUE TO THE 2016 KUMAMOTO EARTHQUAKE

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Abstract

A reinforced concrete building was damaged by the 2016 Kumamoto earthquake. Functional use of the building was not allowed after the earthquake due to tilt and settlement of the building. The building has deep foundation system with precast concrete piles. Several damage investigations were carried out for the foundation system and structural members of superstructure in the building.

Damage investigations for the foundation system were carried out two times. First investigation was carried out for the three piles before demolition of superstructure. Second investigation was carried out for about half the number of piles after demolition of superstructure.

Damage investigations for structural members of superstructure were carried out two times. First investigation was carried out for three hours before removal of interior material, ceiling material and furniture. Second investigation was carried out for two days after removal of interior material, ceiling material and furniture. In order to judge damage level of structural members, damage investigation was carried out by two teams. One team consisted of experts; another team consisted of students.

In this paper, post-earthquake damage evaluations were carried out for the building using above various damage investigation results. Furthermore, differences of the results on post-earthquake damage evaluations were discussed.

The findings of this study are summarized:

(1) Damage investigations for the foundation system were carried out two times. As the results, guessed settlement value using exterior joint line of superstructure from first investigation was underestimated actual foundation settlement from second further investigation. However, tilted direction and can be evaluated using exterior joint line of superstructure.
(2) Intermediate part damage of the pile was not founded in first investigation. However, the damage was observed in second further investigation.
(3) Damage investigations for structural members of superstructure were carried out two times. First investigation was carried out for three hours before removal of interior material, ceiling material and furniture. Second investigation was carried out for two days after removal of interior material, ceiling material and furniture. The result in X-direction is lighter than result of second investigation by expert team, because large shear cracks of structural walls were not observed in first investigation behind gypsum plaster board. The result in Y-direction is heavier than result of second investigation by expert team, because not damage columns were not investigated in first investigation because of short time, furniture or locked room.

Keywords: damage investigation, reinforced concrete building, post-earthquake damage evaluation

1. Introduction

In the 2016 Kumamoto earthquake, some reinforced concrete (hereafter, RC) buildings were damaged due to earthquake vibration. MLIT (Ministry of Land, Infrastructure, Transport and Tourism) reports some government buildings were damaged; therefore, it was difficult that these buildings were used continuously after the earthquake [1]. In this study, several damage investigations were carried out for a RC government building. The building has deep foundation system with precast concrete piles. Functional use of the building was not allowed after the earthquake due to tilt and settlement of the building. Damage investigations were carried out for the foundation system and structural members of superstructure in the building.
In this paper, post-earthquake damage evaluations were carried out for the building using various damage investigation. Furthermore, differences of the results on post-earthquake damage evaluations are discussed.

2. Target building and earthquakes

Target building was in Mashiki town, Kumamoto prefecture, Japan. The building was a three-story RC building with one-story penthouse and constructed in 1980. Floor plan of first floor is shown in Fig. 1. The floor plan has nine spans in the lateral direction and four spans in the longitudinal direction. Connecting corridor two-story RC building was located on the north side of the target building with expansion joint. The target building has deep foundation system with precast concrete piles. The piles have 400mm diameter hollow section. The length of piles were 26 to 32 meters. The pile category was written as PC pile (prestressed concrete pile) or PHC pile (pretensioned spun high strength concrete piles) in structural calculation report of seismic retrofitting. In this report, the long-term allowable bearing capacity of the pile was written as 500kN. The total number of piles were 177; three to six piles were located in each footing. Construction detail of pile and pile head connection was unknown. In 2012, the target building was seismic retrofitted using the adding RC walls and precast retrofit RC frame as shown in Fig. 1. Furthermore, seismic structural gaps were constructed between column and the spandrel wall. The precast retrofit RC frame has deep foundation system with steel pipe piles (318.5mm diameter, 27m length). Two steel pipe piles were located in each footing.

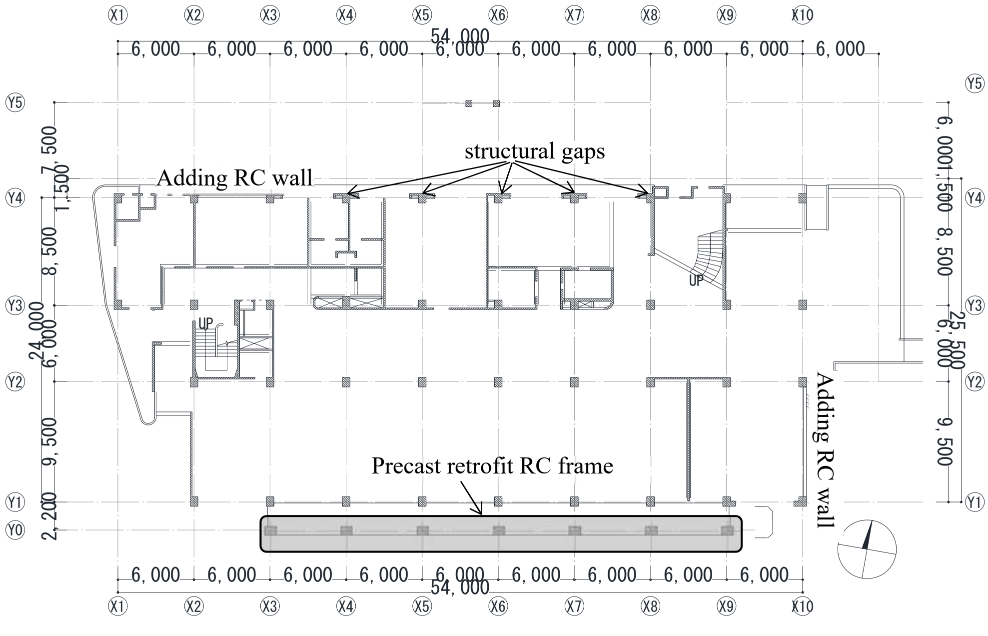


Fig. 1 – Floor plan (unit: mm)

In the foreshock of Kumamoto Earthquake that occurred at 21:26 on April 14th and the mainshock that occurred on April 16th at 01:25. The maximum JMA seismic intensity scale "7" was recorded on the first floor in this building. The building was located in 5.6km north from the epicenter of the foreshock and 6.7km north-east from the epicenter of the mainshock.

3. Damage investigation for the foundation system

Damage investigations for the foundation system were carried out two times. First investigation was carried out for the three piles before demolition of superstructure. Second investigation was carried out for about half the number of piles after demolition of superstructure.

3.1 First Damage investigations for the foundation system

First investigation was carried out for the three piles on August 2016. Damage of pile head and pile location are shown in Fig.2 and Fig.3, respectively. No.1 pile was broken with diagonal clack and shorten in axial direction with longitudinal reinforcements buckling. Connection face of No.2 pile was broken with longitudinal reinforcements buckling. Damage of No.3 pile was not observed by hearing investigation.

(a) No.1(X2, Y1) (b) No.2(X1, Y4)

Fig. 2 –Damage of pile head

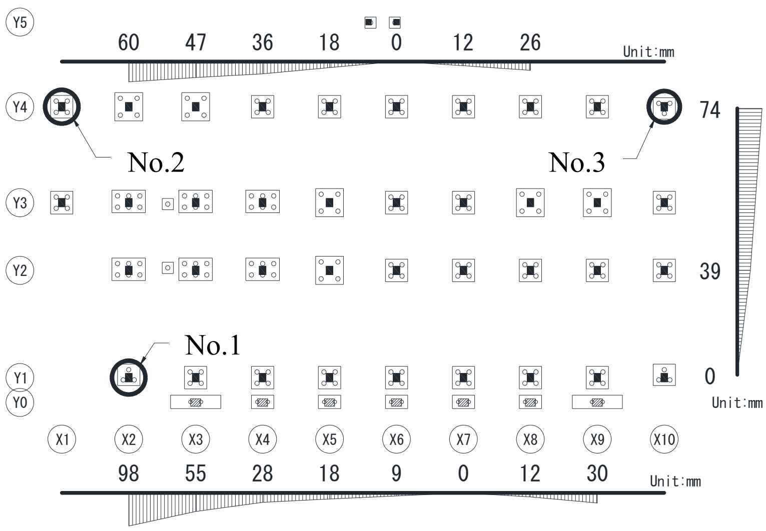


Fig. 3 –Pile location and relative settlement

Building relative settlement of each point is shown in Fig.3. The values were guessed by gap between each point and highest point. The height of points was measured in exterior joint line of each side which was probably horizontal line before earthquake. The maximum settlement value was 98mm at south-west point. The building was tilted to the north side.

3.2 Second Damage investigations for the foundation system

Second investigation was conducted on May 2018. This investigation was carried out for twenty-seven piles and twenty-one footings after demolition of superstructure. Procedure of the investigation is as follows.

1. Demolition of superstructure.
2. Demolition of first floor RC slab, however, foundation beams, footings and piles were not demolished.
3. Digging investigated areas using excavator. (Fig. 4 (a))
4. Digging around the pile to one meter below the level of footing undersurface by manual. (Fig. 4 (b))
5. Observation of foundation beams, footings and piles.

(a) Digging by excavator (b) Digging by manual

Fig. 4 – Digging procedure

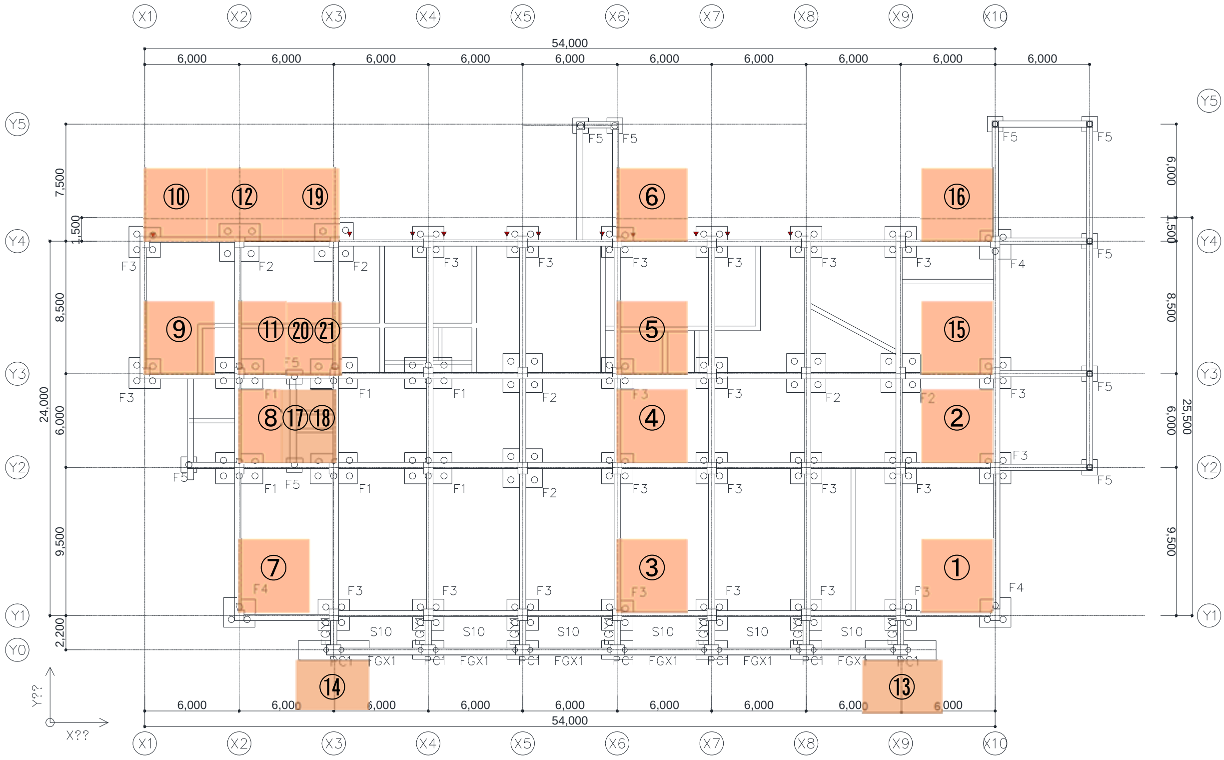


Fig. 5 –Investigation area

The investigated areas are shown in Fig. 5. Typical damage of the piles is shown in Fig. 6. The circled number (1 to 21) in Fig. 5 means ID number of investigated footings. Furthermore, ID number of investigated piles is added branch number to footing ID number. All piles were tilted. All piles expect for a pile (pile ID: 11-1) was tilted to east direction. Tilt angle was 2.6% to 13.7% in east-west direction. One of northwest pile (pile ID: 9-1) was not settled, however, it was slipped in horizontal direction as shown in Fig. 6 (a). Fig. 6 (a) was recorded from north side of the pile. One of southwest pile (pile ID: 14-2) which was attached to precast retrofit RC frame foundation was settled due to steel pipe buckling at pile head as shown in Fig. 6 (b). Fig. 6 (b) was recorded from south side of the pile. One of northeast pile (pile ID: 16-1) was damaged only north side part of the pile head concrete as shown in Fig. 6 (c). Fig. 6 (c) was recorded from north side of the pile. This pile was tilted to south direction (3.6%) and east direction (6.7%). Additional digging (0.7m depth more) was conducted only for this pile. As the result, south side of 1.1m to 1.7m area from pile head was clashed concrete as shown in Fig. 6 (d). Fig. 6 (d) was recorded from west side of the pile. The other piles were not observed intermediate part of the piles; however, many piles were tilted more than 2.0 % as well as 16-1 pile. If the other piles were same condition as 16-1 pile, it is guessed that intermediate part of pile was damaged. 16-1 pile was same pile as No.3 pile which was judged to no damage in first investigation. Thus, intermediate part damage of the pile was not founded in first investigation.

(a) Pile head; ID: 9-1 (X1, Y3) (b) Pile head; ID: 14-2 (X3, Y0)

(c) Pile head; ID: 16-1(X10, Y4) (d) Intermediate part of pile; ID: 16-1(X10, Y4)

Fig. 6 – Damage of pile

Building relative settlement of investigation point are shown in Fig.7. The values were guessed by gap between each point and highest point. The measuring was conducted in existing frame area and in precast retrofit RC frame area, respectively. The height of points was measured top surface of each footing in existing frame. On the other hand, the height of points was measured in top surface of exterior mortar in precast retrofit RC frame area. The maximum settlement value was 194mm at north-west point. The building was tilted to the north side. On the other hand, settlement values at center of frame was small in east-west direction. The settlement values of first and second investigation was different. However, tilted direction and settlement condition were almost same results.

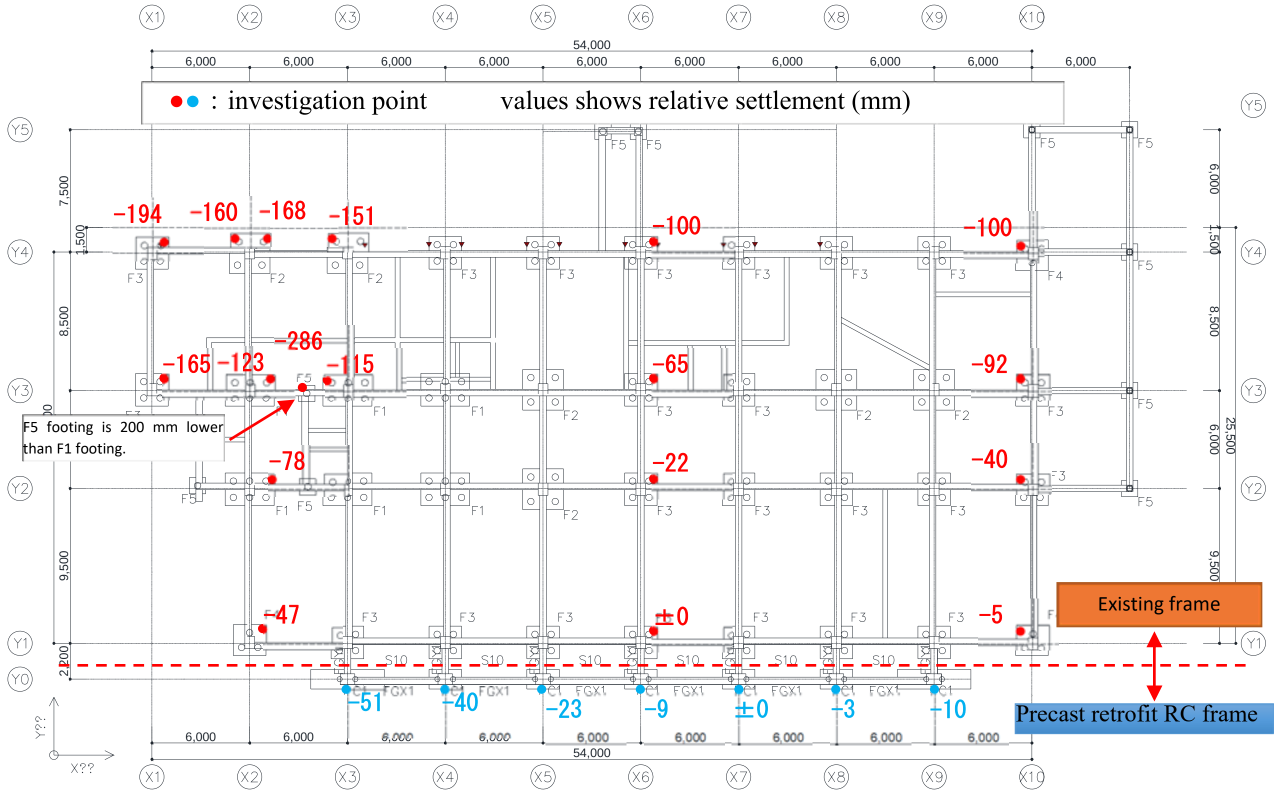


Fig. 7 – Relative settlement (unit: mm)

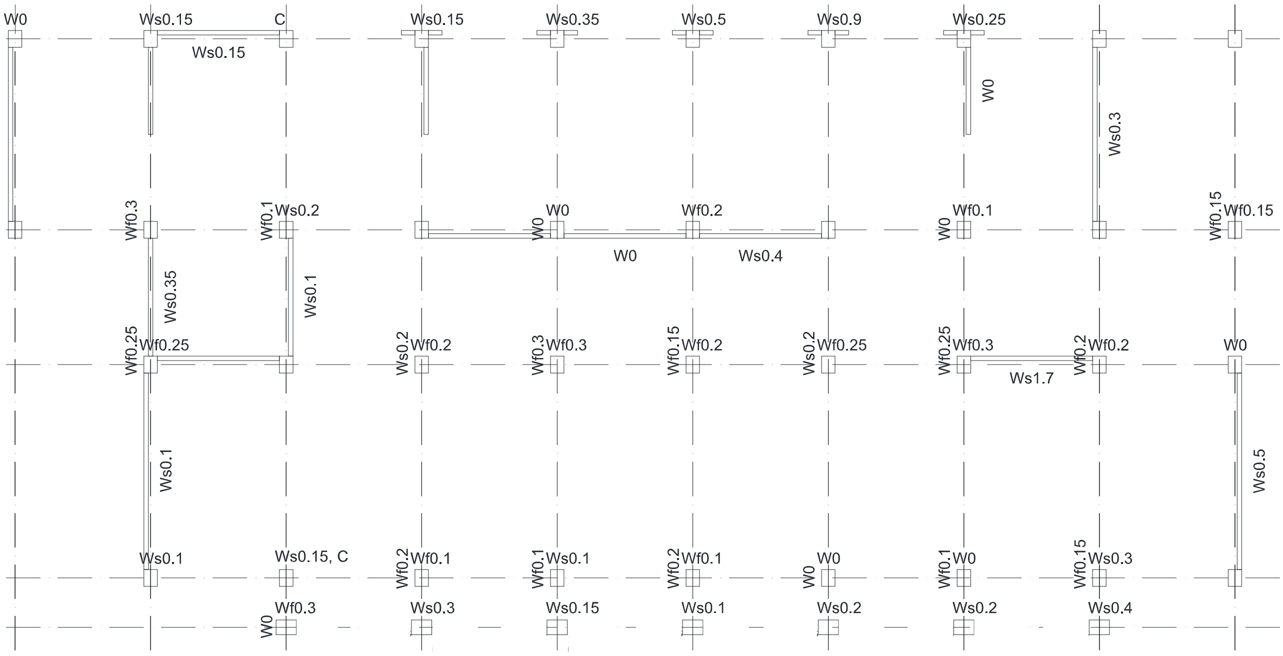
4. Damage investigation for structural members of superstructure

Damage investigations for structural members of superstructure were carried out two times. First investigation was carried out for three hours before removal of interior material, ceiling material and furniture. Second investigation was carried out for two days after removal of interior material, ceiling material and furniture. In order to judge damage level of structural members, damage investigation was carried out by two teams. The teams used manual measurement methods. One team consisted of experts of structural engineering (hereafter, expert team); another team consisted of undergraduate and graduate students (hereafter, student team).

4.1 First investigation by expert team

First damage investigation for structural members of superstructure were carried out by two experts. The investigation was carried out for three hours before removal of interior material, ceiling material and furniture. Damage level of columns and walls were judged only first floor, because of short time of investigation. Furthermore, some structural member was not observed because of furniture or locked room. Damage of inside beam was not investigated because of ceiling material. However, outside beam (connecting existing frame and precast retrofit RC frame) can be observed as shown in Fig. 8. Damage of structural members are shown in Fig. 9. Cracks of columns and walls were measured over interior material. Generally, damage investigation after earthquake is conducted under same condition. Shear crack width 1.7mm was observed at X direction wall (X8-X9, Y2). Visible shear crack was observed at Y direction outside beams as shown in Fig. 8. The crack width was not measured directly, because of high. However, the crack width was judged about 2.0mm by visual inspection of expert team.

Fig. 8 – Shear crack of beam to connect existing frame and precast retrofit RC frame



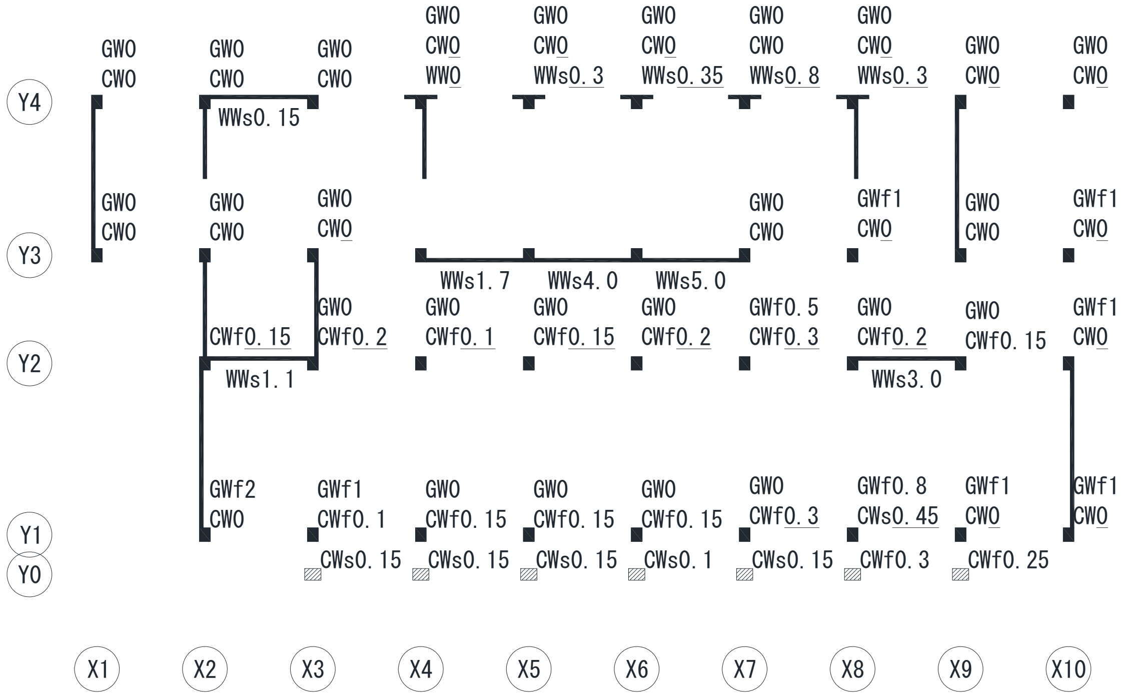
Wf : flexral crack width	Ws : Shear crack width	C : crushed concrete

Fig. 9 – Damage of structural members (First investigation)

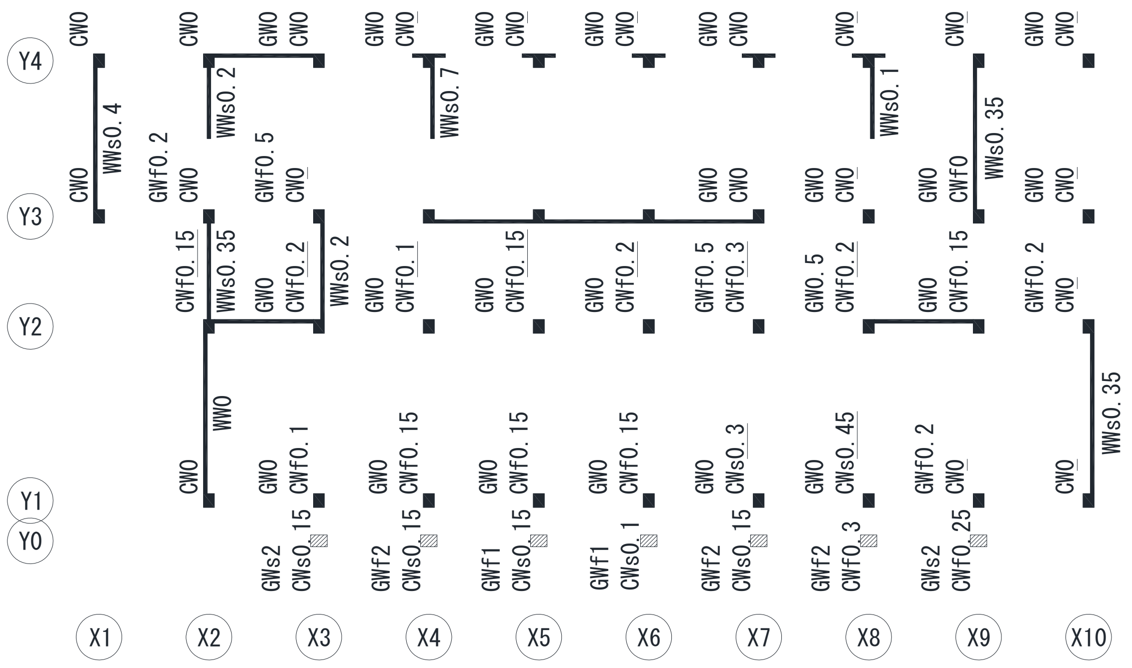
4.2 Second investigation by expert team

Second investigation was carried out for two days after removal of interior material, ceiling material and furniture. Expert team conducted damage investigation for all columns, all walls and all beams on all floor. They masured concrete crack width directly because of removal of interior material. The muximum crack width of each member was mesured using card type crack scale in each structural member. However, the muximum crack width of each beam was judged by visual inspection. This condition is ideal condition for damage investigation of structral member. Damage of structural members on first floor is shown in Fig. 10.

Shear crack width 1.7, 4.0 or 5.0mm were observed at X direction walls (X4-X7, Y3), respectively. These cracks were not observed in first investigation behind gypsum plaster board. Many columns of north area were not damaged in Y direction. These columns were not investigated in first investigation because of short time, furniture or locked room.



(a) Results of X-direction



(b) Results of Y-direction

First caractor shows type of member	C: Column	G: beam	W: Wall
Second and third caractor shows type of crack	Wf : flexral crack	Ws : shear crack	
The value without under bar shows actual crack width			
The value with under bar shows measured crack over interior material			

Fig. 10 – Damage of structural members on first floor (Second investigation, expert team)

Table 1 – Relationship between actual crack and measured crack over interior material

Position	Finishing	Finishing thickness (mm)	Crack	actual crack width (mm)	measured crack width (mm)	Position	Finishing	Finishing thickness (mm)	Crack	actual crack width (mm)	measured crack width (mm)
X3-Y1-1F	Mortar	12	Flexural	0.10	0.25	X7-Y1-3F	Mortar	12	Flexural	0.05	0.10
X4-Y1-1F	Mortar	12	Flexural	0.10	0.25	X7-Y1-3F	Mortar	30	Flexural	0.10	0.35
X4-Y1-1F	Mortar	12	Flexural	0.10	0.15	X7-Y1-3F	Mortar	30	Flexural	0.05	0.20
X5-Y1-1F	Mortar	12	Flexural	0.15	0.40	X7-Y1-3F	Mortar	30	Flexural	0.05	0.15
X6-Y1-1F	Mortar	30	Flexural	0.10	0.35	X7-Y1-3F	Mortar	30	Flexural	0.00	0.10
X6-Y1-1F	Mortar	30	Flexural	0.10	0.35	X8-Y1-3F	Mortar	20	Flexural	0.00	0.10
X7-Y1-1F	Mortar	30	Flexural	0.05	0.15	X8-Y1-3F	Mortar	20	Flexural	0.00	0.15
X4-Y1-2F	Mortar	25	Flexural	0.15	0.45	X2~3-Y3-2F	Mortar	-	Shear	0.35	0.50
X5-Y1-2F	Mortar	-	Flexural	0.10	0.25	X2~3-Y3-2F	Mortar	-	Shear	0.35	0.60
X6-Y1-2F	Mortar	-	Flexural	0.10	0.20	X2~3-Y3-2F	Mortar	-	Shear	0.25	0.50
X6-Y1-3F	Mortar	20	Flexural	0.05	0.20	X2~3-Y3-2F	Mortar	-	Shear	0.20	0.35
X6-Y1-3F	Mortar	20	Flexural	0.00	0.15	X2~3-Y3-2F	Tilement	-	Shear	0.50	2.00
X6-Y1-3F	Mortar	20	Flexural	0.00	0.20	X4~5-Y3-3F	Gypsum board	-	Shear	0.80	0.80
X6-Y1-3F	Mortar	20	Flexural	0.05	0.20	X2~3-Y3-3F	Gypsum board	-	Shear	1.30	1.30
X6-Y1-3F	Mortar	20	Flexural	0.10	0.20						

(a) RC column with mortar finishing (b) RC wall with gypsum plaster board

Fig. 11 – structural member with interior material

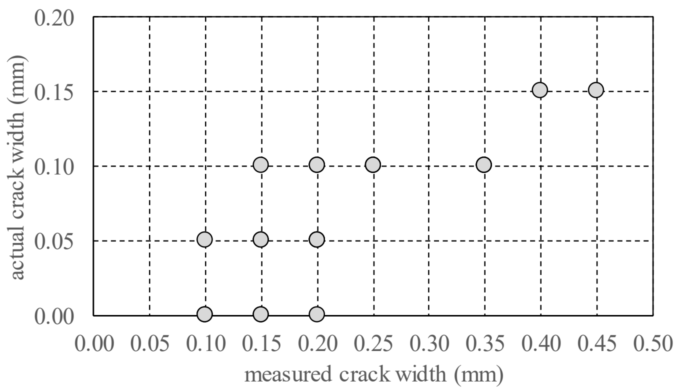


Fig. 12 – Relationship between actual crack and measured crack over mortar finishing

In many case of structural member, interior material was removed, however, in some case of structural member, interior material was not removed. Some cracks were crossovered between interior material area and interior material removed area as shown in Fig. 11. Relationship between actual crack and measured crack over interior material is shown in Table 1. The actual crack width was measured in interior material removed area. The measured crack over interior material was measured in interior material area. Twenty-two flexural crack were mesured over mortar finishing as sample data. There were not enough data for the other type crack. Relationship between actual crack and measured crack over mortar finishing is shown in Fig. 12. The measured crack width over mortar finishing were 0.1 to 0.45 mm, however, the actural crack width were less than 0.20 mm. Thus, if measured crack width over mortar finishing is less than or equal to 0.45mm, actural crack width is judged to be less than 0.20mm for post-earthquake damage evaluation in chapter 5.

4.3 Second investigation by student team

Student team conducted damage investigation for walls on all floor and for columns only first floor. They mesured crack width and concrete floating or spalling area. Investigation area of columns and walls was 0 to 2.0m height from floor level. Crack was traced to structural member using permanent marker. The muximum flexral/shear crack width was mesured using card type crack scale in each structural member. The mesured point of crack width was marked using permanent marker. Damage of structural members is shown in Fig. 13 and Fig. 14.

Shear crack width 1.3, 0.9 or 0.4mm was observed at X direction walls (X4-X7, Y3), respectively. On the other hand, 1.7, 4.0 or 5.0 was measured by expert team in the same walls. Because these cracks were measured upper 2.0 m height by expert team. Many columns of north area were not investigated. These columns were not damaged according to second investigation by expert team.

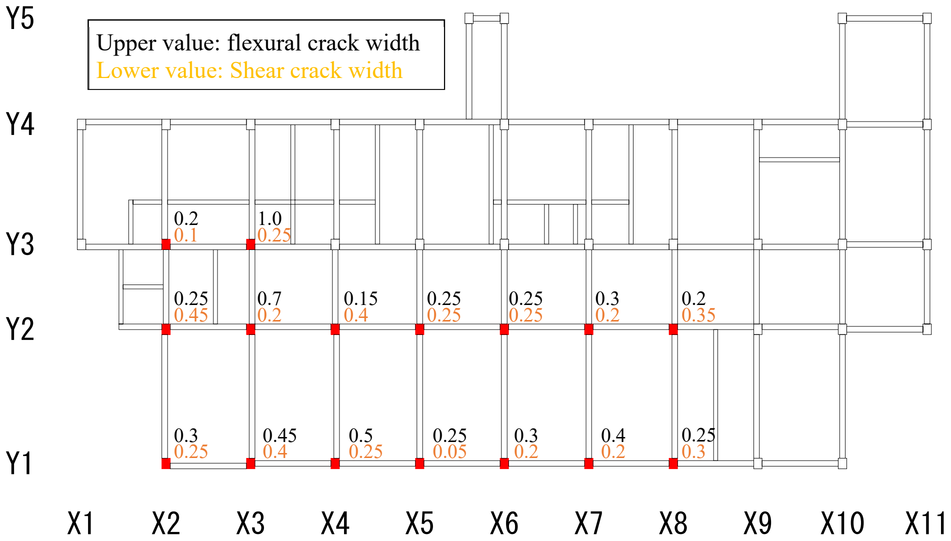


Fig. 13 – Damage of Column on first floor (Second investigation, student team)

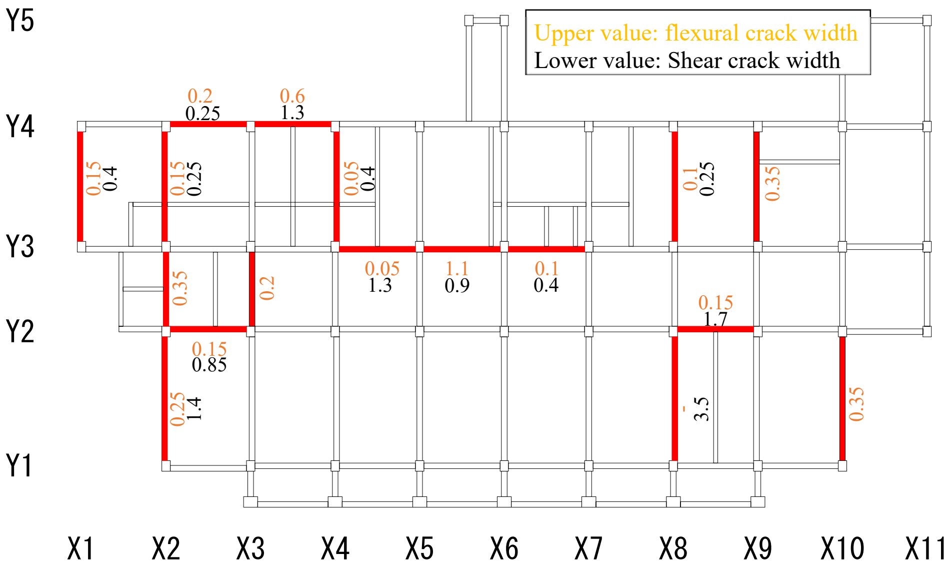


Fig. 14 – Damage of Wall on first floor (Second investigation, student team)

5. Post-earthquake damage evaluation and discussion

4.1 For foundation system

In first investigation, settlement value was measured using exterior joint line. In second investigation, settlement value was measured using top surface of each footing in existing frame. The settlement values of first and second investigation was different. However, tilted direction and settlement condition were almost same results. The maximum settlement value and the maximum tilted angle are calculated for each investigation, using each measured settlement values. The results are shown in Table 2. The maximum settlement value was changed 98mm to 194mm. The maximum tilted angles (X-direction) of each investigation are almost same value. The maximum tilted angles (Y-direction) was changed 0.41% to 0.87%. Damage classification criteria for foundations [2] is shown in Table 3. The classified damage was changed moderate damage to severe damage. Thus, guessed settlement value using exterior joint line of superstructure was underestimated actual foundation settlement. However, tilted direction and can be evaluated using exterior joint line of superstructure.

Table 2 – The maximum settlement value and the maximum tilted angle

	The maximum settlement value (mm)	The maximum tilted angle (%)	
		X-direction	Y-direction
First investigation	98mm (X2, Y1)	0.72% (X2-X3, Y1)	0.41% (X10, Y1-Y2)
Second investigation	194mm (X1, Y4)	0.70% (X1-X2, Y3)	0.87% (X10, Y2-Y3)

Table 3 – Damage classification criteria for foundations [2]

Tilt angle (%)	Settlement of foundation (m): below 0	0 – 0.1	0.1 – 0.3	above 0.3
below 0.333	No damage	Minor Damage	Moderate Damage *	**
0.333 – 0.667	Minor Damage	Moderate Damage	Moderate Damage	Severe Damage
0.667 – 1.333	Moderate Damage	1st Moderate Damage	2nd Severe Damage	Severe Damage
above 1.333	Severe Damage	Severe Damage	Severe Damage	Severe Damage

*: Further investtigation (visual inspection for pile) is nesessary under some condition[2].
**: This case is not covered, further investtigation (visual inspection for pile) is nesessary.

4.2 For structural members of superstructure

The results of post-earthquake damage evaluation for structural members of superstructure are shown in Table 4. In this study, the results of post-earthquake damage evaluation from second damage investigation by expert team can be regarded as actual damage of the building. Thus, the results of post-earthquake damage evaluation from first damage investigation by expert team and second damage investigation by student team are discussed, respectively as follows.

(a) The results of post-earthquake damage evaluation from first damage investigation by expert team
In X-direction, damage classification is "Moderate". The result is lighter than result of second investigation by expert team, because large shear cracks of structural walls were not observed in first investigation behind gypsum plaster board. In Y-direction, damage classification is "Moderate". The result is heavier than result of second investigation by expert team, because not damage columns were not investigated in first investigation because of short time, furniture or locked room.

(b) The results of post-earthquake damage evaluation from second damage investigation by student team

In X-direction on first floor, damage classification is “Severe”. The result is same as result of second investigation by expert team, because large shear cracks of structural walls were not observed in first investigation behind gypsum plaster board. In Y-direction on first floor, damage classification is “Moderate”. The result is heavier than result of second investigation by expert team, because of same reason as first damage investigation. On the other hand, second and third floor, only wall were investigated. In this building, damage of walls is heavier than damage of columuns. Thus,the results of damage classification in second and third floor are heavier than result of second investigation by expert team.

Table 4 – Results of post-earthquake damage evaluation

	1F		2F		3F	
	X-Dir.	Y-Dir.	X-Dir.	Y-Dir.	X-Dir.	Y-Dir.
First investigation	Moderate (74.6)	Moderate (73.8)				
Second investigation by student team	Severe (53.4)	Moderate (65.1)	Severe (46.2)	Moderate (76.7)	Severe (56.1)	Moderate (71.1)
Second investigation by expert team	Severe (50.6)	Minor (87.9)	Moderate (78.6)	Minor (84.6)	Moderate (74.2)	Minor (87.4)

* bracketed value shows residual seismic capacity ratio index "R"

6. Conclusion

A reinforced concrete building was damaged by the 2016 Kumamoto earthquake. Several damage investigations were carried out for the foundation system and structural members of superstructure in the building. The findings of this study are summarized:

(4) Damage investigations for the foundation system were carried out two times. As the results, guessed settlement value using exterior joint line of superstructure from first investigation was underestimated actual foundation settlement from second further investigation. However, tilted direction and can be evaluated using exterior joint line of superstructure.

(5) Intermediate part damage of the pile was not founded in first investigation. However, the damage was observed in second further investigation.

(6) Damage investigations for structural members of superstructure were carried out two times. First investigation was carried out for three hours before removal of interior material, ceiling material and furniture. Second investigation was carried out for two days after removal of interior material, ceiling material and furniture. The result in X-direction is lighter than result of second investigation by expert team, because large shear cracks of structural walls were not observed in first investigation behind gypsum plaster board. The result in Y-direction is heavier than result of second investigation by expert team, because not damage columns were not investigated in first investigation because of short time, furniture or locked room.

7. Acknowledgements

A lot of information showed in this paper were provided from Mashiki town in Kumamoto. And also, the damage investigation was conducted with the cooperation of the local government and Building Research Institute of Japan. We would like to express our gratitude to all it may concern and to the committees involved.

8. References

[1] Ministry of Land, Infrastructure, Transport and Tourism, “Committee report for building damage in the 2016 Kumamoto earthquake”, 2016.9, (in Japanese) (http://www.mlit.go.jp/report/press/house05_hh_000633.html)

[2] The Japan Building Disaster Prevention Association (JBDPA), “Guideline for Post-earthquake Damage Evaluation and Rehabilitation”, 1991 (revised in 2001). (in Japanese)

