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Strong Ground Motions and Damage Investigation of Buildings near the Surface Faulting of the 2016 Kumamoto Earthquake in Japan

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Abstract

This paper reports characteristics of the strong ground motion records and the results for investigating building damage near the surface faulting of the 2016 Kumamoto earthquake. The EW components of the strong motions in Mashiki City and Nishihara Village were dominant at periods longer than 1-2 sec, and showed clearly the fling steps; they were caused by the motion of the hanging wall of the normal/right-lateral faulting, and were dominant in the direction of the faulting slip. The forward directivity pulses, on the contrary, which were dominant in the direction normal to the fault plane (close to the NS components), were not very clear in the records. This is probably due to the complex faulting process and/or the propagation effects of the seismic waves in the local complex media. On the other hand, the records of the EW components in the Mashiki City showed the large amplitudes at about 1 sec; they were probably the forward directivity pulses.

The results of the building investigation indicated that most of severe damage occurred in those directly above the surface faulting, because of its slip deformation. And, almost all severe damaged buildings were very old wooden houses/apartments, whereas new wooden or RC buildings showed very minor damage. In the Shimojin area, particularly, the ground motion was probably not strong enough to cause severe damage, and thus, the highest damage was Grade 3. All of them were very old wooden buildings and directly above the surface faulting. Even though the best counter measure for buildings near active faults is to avoid them, it is unrealistic to prohibit buildings in such areas shown in this study, because the exact locations of the surface faulting are very difficult to identify. In fact, they differed from those of the actual surface faulting, because of the young alluvial/volcanic sediments and the artificial land development. In addition, the recurrence intervals of the active faults are extremely long (usually several thousand years), as compared with the lifetime of a building. And the most importantly, various safety counter measures are effective, even for the building directly above the surface faulting. For example, the new wooden houses with the mat foundation of RC could prevent the slip deformation from reaching the building, and the combinations of the shear wall and light roofs prevented severe damage. On the other hand, the old Japanese traditional houses generally suffered severe damage, but their structural flexibilities could prevent collapsing by following the slip deformation. The collapsed buildings were generally very old and lacked both the sufficient earthquake-resisting structural members and the effective connections among them.

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Keywords: the 2016 Kumamoto Earthquake; Strong Motion Records; Active Fault; Surface Faulting; Building Damage

1. Introduction

As shown in Fig.1 and Table 1, a series of M6-7 earthquakes occurred from April 14 to 16 in 2016 along the Futagawa and Hinagu fault zones in the Kumamoto prefecture of the Kyushu Island, Japan, and caused destructive damage in the local areas[1)]. The main-shock (M_W7.0/M_{JMA}7.3, 2016/4/16) generated the extensive surface faulting, and recorded characteristic near-fault strong ground motions in Mashiki City and Nishihara Village. We investigated more than 200 buildings near the surface faulting in May 7, 8, and 25 in 2016, and this paper reports the characteristic strong ground motions and the results of the investigation.

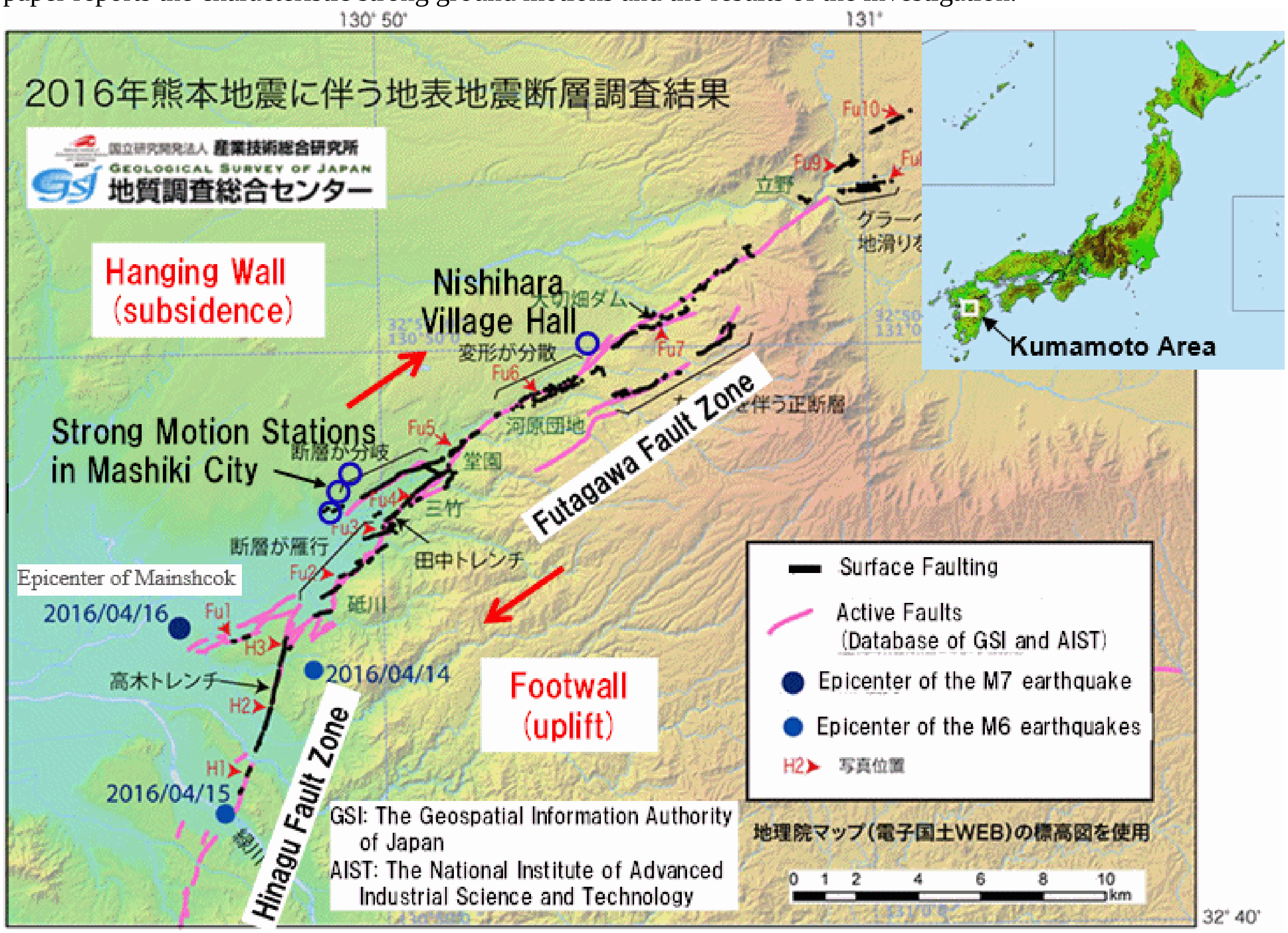


Fig. 1 – The active faults, the surface faulting and the strong motion recording sites of the Kumamoto earthquake (from Geological Survey of Japan: https://www.gsj.jp/hazards/earthquake/kumamoto2016/)

Table 1 – The fault parameters of the main and forshocks of the Kumamoto earthquake [1*]

Date and Time (Local and UTC)	Hypocenter	depth	Magnitude (Mj/Mw)	JMA Seismic Intensity (Max)
14 April 2016 21:26 JST (12:26 UTC)	(32.742N, 130.808E) [2*]	11 km	6.5/6.2	7
15 April 2016 00:03 JST (14 April 2016 15:03 UTC)	(32.700N, 130.777E) [3*]	10 km	6.4/6.0	6+
16 April 2016 01:25 JST (15 April 2016 16:25 UTC)	(32.753N, 130.762E) [4*]	12 km	7.3/7.0	7

1* from JMA: http://www.jma.go.jp/jma/en/2016_Kumamoto_Earthquake/2016_Kumamoto_Earthquake.html
2* from NIED: http://www.kyoshin.bosai.go.jp/kyoshin/topics/html20160414212621/main_20160414212621.html
3* from NIED: http://www.kyoshin.bosai.go.jp/kyoshin/topics/html20160415000310/main_20160415000310.html
4* from NIED: http://www.kyoshin.bosai.go.jp/kyoshin/topics/html20160416012405/main_20160416012405.html

2. Strong Ground Motion Records near the Surface Faults

First, we report the characteristic strong ground motions recorded near the surface faults. Fig.2(a) and (b) show the strong ground motion records of the main-shock at the three sites in Mashiki City (KMMH16 of KiK-net Mashiki[2)], Mashiki City hall of JMA[3)], and TMP3 of Hata *et.al.*[4)], and at the Nishihara Village hall (JMA[3)]), respectively. They are the original accelerations, velocities (corrected the base lines), displacements, velocity response spectra, and velocity orbits on the horizontal plane. The displacements at all the sites show clearly the fling steps on the hanging wall of the normal and right-lateral faulting[5), 6)], which are dominant in the EW components at longer periods. In addition, the records at the city hall and TMP3 sites in Mashiki City show the very large amplitudes around 1 sec in the EW direction, which caused the heavy building damage in this area[1)] ; this destructive strong motion was probably the forward directivity pulses[7)].

3. Damage Investigation of Buildings near the Surface Faults

Next, we show the results for investigating building damage near the surface faulting. Fig.3 shows the three investigation areas (Takagi, Shimojin, and Kurokawa), and the locations of the surface faults (black lines) and other surface cracks (red lines)[8)].

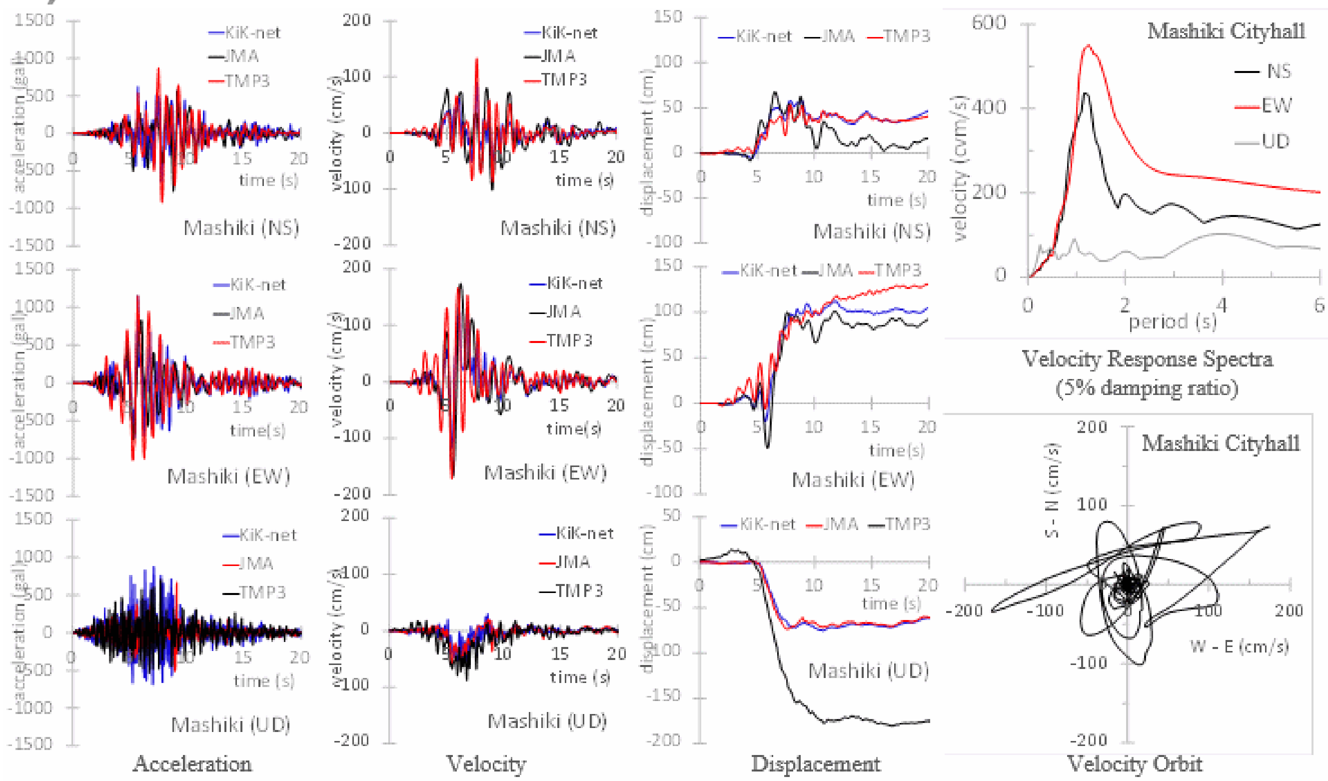
Figs.4 shows the locations of the investigated building (solid lines) and warehouses (dotted lines) at the three areas, together with the surface faulting (red lines) and the active faults/ground cracks (black lines)[8)]. We understand the differences of the locations between the active faults and the identified surface faulting in the Takagi (Fig.4(a)) and Shimojin areas (Fig.4(b)). In addition, we see complex distribution of the surface faulting and the other ground cracks at the Kurokawa area (Fig.4(c)), where the active faults were not known prior to the Kumamoto earthquake. Those results indicate how difficult to identify the exact locations of the surface faulting before occurring large earthquakes in such complex geological and geographical areas of young alluvial and volcanic sediments covered by artificial residential land developments.

We carried out the visual inspection of buildings and warehouses near the surface faulting in May 7, 8, and 25 in 2016, by checking the building age (new (less than about 10 years old), old (about 10 – 30 years old), or, very old (older than about 30 years old)), structures (wooden, steel, or, RC), use (residential, office, *et al.*), stories, foundations (individual, continuous footing, or, mat foundation), the damage grade, and detail of damage. The damage grade are classified to 1 (slight damage), 2 (moderate damage), 3 (substantial damage), 4 (very heavy damage), 5 (destructive damage), and 6 (total collapse) [9)]. Since most of the warehouses are very old non-engineered structures, which show much more severe damage than the regular building, we use only the data of the buildings excluding of warehouses in this paper.

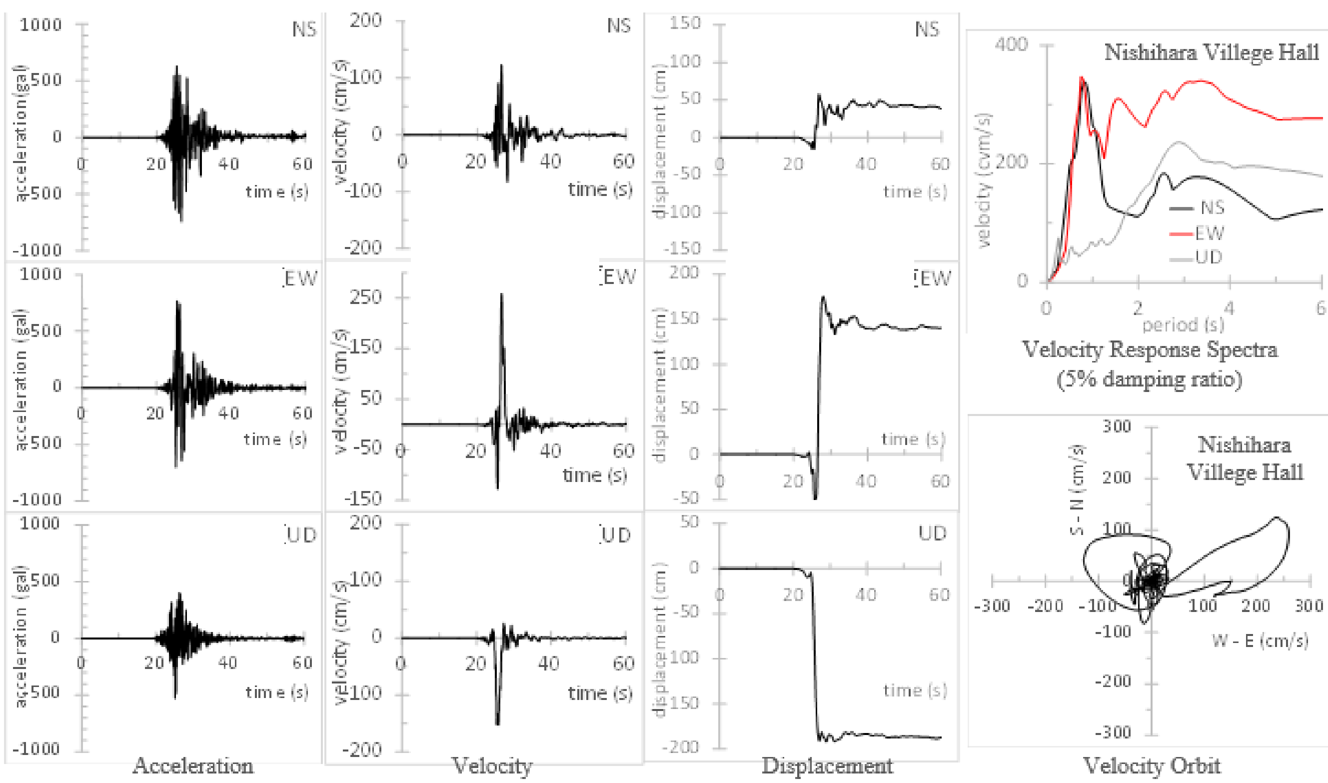
3.1 Building Damage in the Takagi Area

Table 2 and Fig.5 show the statistics of 39 buildings and the pictures of three buildings in the Takagi area (see the location in Fig.3). The three buildings (a) – (c) in Fig.5 are located upon the surface faulting (see their locations in Fig.4(a)). As shown in Table 2, 90% of the investigated buildings are wooden houses with 2 stories and less. In this area, we found only one collapsed building (Damage Grade 5), which was very old wooden post office. Among 39 buildings, the number and the ratio of the severely damaged buildings (Damage Grade 4 and over) are 7 and 18%, respectively. There are 7 buildings, which are directly above the surface faulting, and 43% (3 buildings) of them are severely damaged. On the other hand, there are 32 buildings which are not above the surface faulting, and 13% (4 buildings) are severely damaged. Similarly, the ratios (numbers) of the severely damaged buildings for the new, old, and very old buildings are 0% (0), 17% (2), and 29% (5), respectively.

Fig.5(a) is an old wooden building on the surface faulting, and close up of the foundation damage. Due to the lateral fault slip of about 50 cm, the foundation of unreinforced concrete blocks are destroyed. This deformation directly transfers into the building, and causes severe structural damage (Damage Grade 4).



(a) The strong motion records of the main shock at the three sites in Mashiki City (see the locations in Fig.1)[2)-4)]



(b) The strong motion records of the main shock at the Nishihara Village hall (see the locations in Fig.1)[3)]

Fig. 2 – The strong motion records near the surface faulting of the main-shock of the Kumamoto earthquake (accelerations, velocities, displacements, velocity response spectra, and velocity orbits on the horizontal plane)

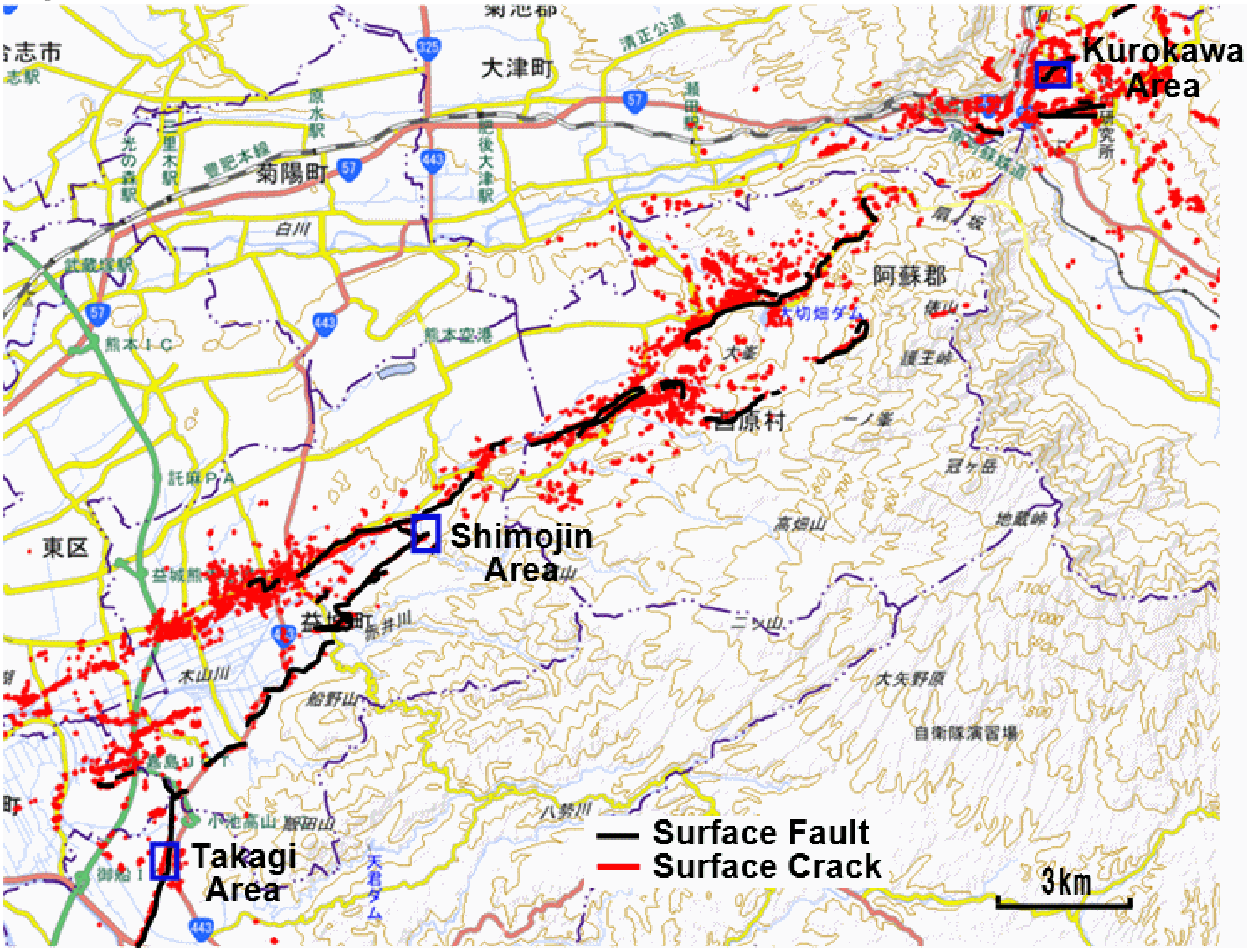


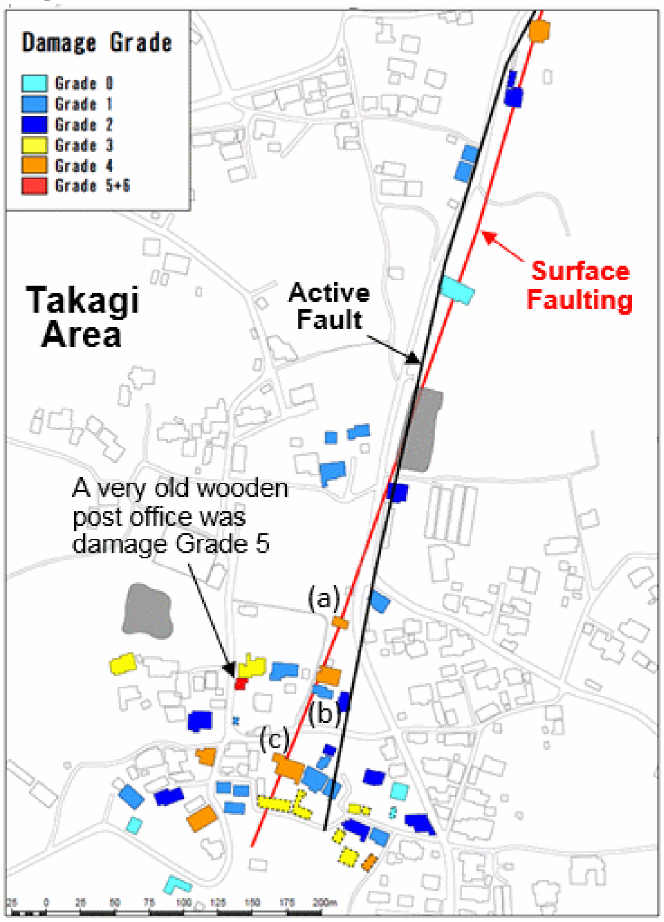
Fig. 3 – The three areas for investigation building damage in this paper, together with the surface faults (black lines) and the surface cracks (red lines), which appeared during the 2016 Kumamoto earthquake (from Geospatial Information Authority of Japan: http://www.gsi.go.jp/BOUSAI/H27-kumamoto-earthquake-index.html)

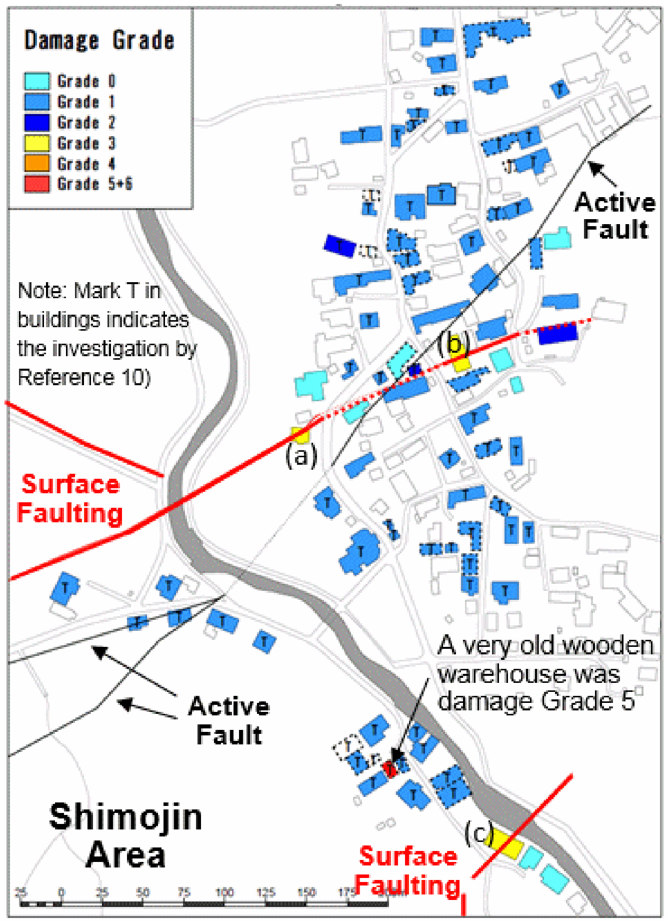
Fig.5(b) shows the front and back of a new light-steel house on the surface faulting. Even though the fault slip of about 50 cm was observed next to the building, the damage was very minor (Grade 1); a few cracks were found on the foundation. This is probably because that the mat foundation of reinforce concrete combined with the rigid shear walls and light root was robust enough to prevent the ground slip from entering into the building.

Fig.5(c) shows the front and back of a very old traditional wooden house on the surface faulting. Contrary to Fig.5(b), the individual footings moved by following the fault slip of about 50 cm, and the building was heavily deformed (Damage Grade 4).

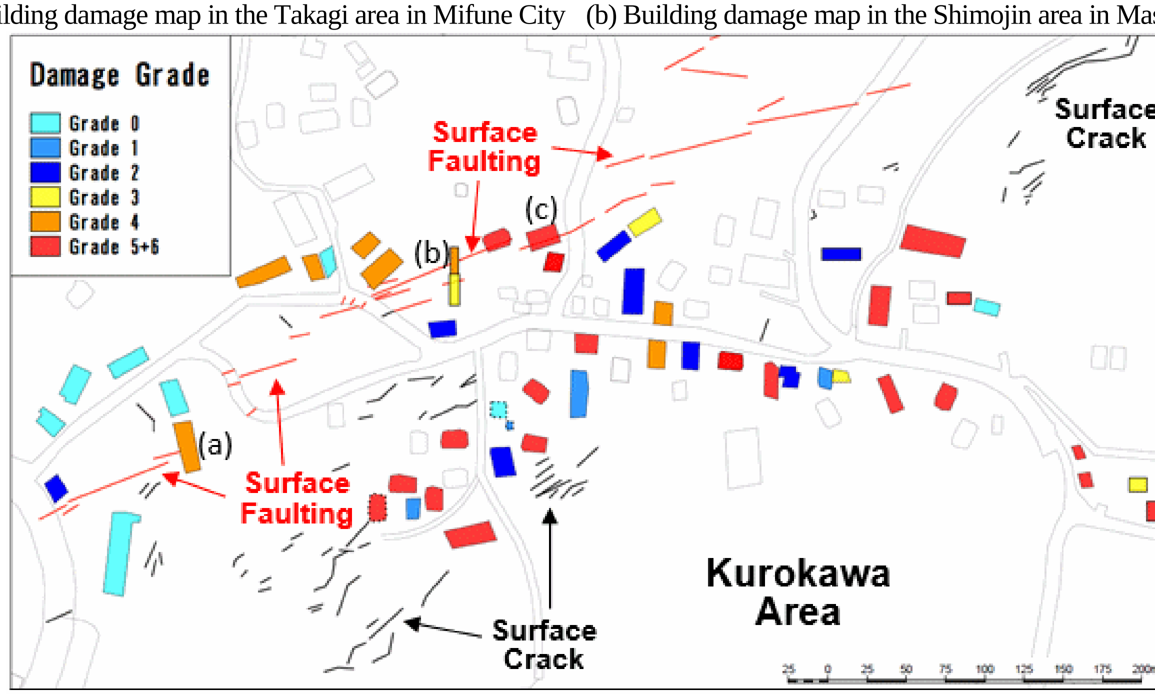
3.2 Building Damage in the Shimojin Area

Table 3 and Fig.6 show the statistics of 61 buildings and the pictures of the three buildings in the Shimojin area (see the location in Fig.3). The three buildings (a) – (c) in Fig.6 are located directly above the surface faulting (see their locations in Fig.4(b)). In addition to our data, we use the data of 44 buildings from the reference[10]. As shown in Table 3, 92% of the buildings are wooden houses with two stories and less. There are no buildings





(a) Building damage map in the Takagi area in Mifune City (b) Building damage map in the Shimojin area in Mashiki City



(c) Building damage map in the Kurokawa area in Aso City

Fig. 4 – The three maps of the building damage and the surface faults
(see the locations of the maps in Fig.3, and the pictures of the buildings (a) – (c) in Figs 5 - 7)

Table 2 – Statistical data of the investigated buildings in the Takagi area

Structure	Number	Ratio
wooden	35	90%
steel	3	8%
RC	1	3%
Total	39	100%

Story	Number	Ratio
1	18	46%
2	21	54%
Total	39	100%

Building Age	Number	Ratio
very old	17	44%
old	12	31%
new	10	26%
Total	39	100%

All Buildings		
Damage Grade	Number	Ratio
Grade 0	4	10%
Grade 1	16	41%
Grade 2	9	23%
Grade 3	3	8%
Grade 4	6	15%
Grade 5	1	3%
Grade 6	0	0%
Total	39	100%
G4 and over	7	18%
G5 and over	1	3%

Buildings on Surace Faulting		
Damage Grade	Number	Ratio
Grade 0	1	14%
Grade 1	1	14%
Grade 2	2	29%
Grade 3	0	0%
Grade 4	3	43%
Grade 5	0	0%
Grade 6	0	0%
Total	7	100%
G4 and over	3	43%
G5 and over	0	0%

Not on Surface Faulting		
Damage Grade	Number	Ratio
Grade 0	3	9%
Grade 1	15	47%
Grade 2	7	22%
Grade 3	3	9%
Grade 4	3	9%
Grade 5	1	3%
Grade 6	0	0%
Total	32	100%
G4 and over	4	13%
G5 and over	1	3%

New Buildings		
Damage Grade	Number	Ratio
Grade 0	4	40%
Grade 1	5	50%
Grade 2	1	10%
Grade 3	0	0%
Grade 4	0	0%
Grade 5	0	0%
Grade 6	0	0%
Total	10	100%
G4 and over	0	0%
G5 and over	0	0%

Old Buildings		
Damage Grade	Number	Ratio
Grade 0	0	0%
Grade 1	6	50%
Grade 2	3	25%
Grade 3	1	8%
Grade 4	2	17%
Grade 5	0	0%
Grade 6	0	0%
Total	12	100%
G4 and over	2	17%
G5 and over	0	0%

Very Old Buildings		
Damage Grade	Number	Ratio
Grade 0	0	0%
Grade 1	5	29%
Grade 2	5	29%
Grade 3	2	12%
Grade 4	4	24%
Grade 5	1	6%
Grade 6	0	0%
Total	17	100%
G4 and over	5	29%
G5 and over	1	6%

exceeds Damage Grade 4 (except a very old warehouse), even for the buildings above the surface faulting; this indicates the local ground motion during the earthquakes was not very severe. Among 61 buildings, only three buildings are Damage Grade 3; they are all very old and directly above the surface faulting (see the locations and pictures in Fig.4(c) and Fig.6, respectively).

Fig.6(a) is a very old wooden building (the left in the picture) on the surface faulting of 20 – 30 cm slip, which shows substantial damage in the foundation due to the ground deformation (Damage Grade 3)[10)]. On the contrary, the new warehouse, which is the right of the picture and out of the ground slip shows little damage.

In Fig.6(b), the left picture shows the frontal view of a very old wooden house (about 100 years old[10)]), and the right picture is the very old warehouse in the backyard. Even though they are directly above the surface faulting, they seemed little damage from these visual inspections. However, the detail investigation reported that a main column was out of the footing and the structure was severely deformed[10)]. We judged the damage of the house to be Grade 3 on the basis of our visual inspection and the report[10)].

Fig.6(c) shows pictures of a very old house (about 80 to 100 years old[10)]) and the surface faulting of 50 – 60 cm slip, which is about 300 m away and parallel to the faulting of Figs.6(a) and (b). The left, center, and right pictures show the surface faulting (front) and the house (back), the frontal view of the house, and the close up of the surface faulting and the building damage, respectively. The detail investigation of the house reported that the fault slip deforms its main structures (foundation, columns, and beams)[10)]. Again, we judged the damage of the house to be Grade 3 on the basis of our visual inspection and the report[10).]

Table 3 – Statistical data of the investigated buildings in the Shimojin area

Structure	Number	Ratio
wooden	56	92%
steel	4	7%
RC	1	2%
Total	61	100%

Story	Number	Ratio
1	18	30%
2	43	70%
Total	61	100%

Building Age	Number	Ratio
very old	14	23%
old	29	48%
new	18	30%
Total	61	100%

All Buildings		
Damage Grade	Number	Ratio
Grade 0	7	11%
Grade 1	49	80%
Grade 2	2	3%
Grade 3	3	5%
Grade 4	0	0%
Grade 5	0	0%
Grade 6	0	0%
Total	61	100%
G4 and over	0	0%
G5 and over	0	0%

Buildings on Surace Faulting		
Damage Grade	Number	Ratio
Grade 0	0	0%
Grade 1	1	20%
Grade 2	1	20%
Grade 3	3	60%
Grade 4	0	0%
Grade 5	0	0%
Grade 6	0	0%
Total	5	100%
G4 and over	0	0%
G5 and over	0	0%

Not on Surface Faulting		
Damage Grade	Number	Ratio
Grade 0	7	13%
Grade 1	48	86%
Grade 2	1	2%
Grade 3	0	0%
Grade 4	0	0%
Grade 5	0	0%
Grade 6	0	0%
Total	56	100%
G4 and over	0	0%
G5 and over	0	0%

New Buildings		
Damage Grade	Number	Ratio
Grade 0	2	11%
Grade 1	15	83%
Grade 2	1	6%
Grade 3	0	0%
Grade 4	0	0%
Grade 5	0	0%
Grade 6	0	0%
Total	18	100%
G4 and over	0	0%
G5 and over	0	0%

Old Buildings		
Damage Grade	Number	Ratio
Grade 0	1	3%
Grade 1	27	93%
Grade 2	1	3%
Grade 3	0	0%
Grade 4	0	0%
Grade 5	0	0%
Grade 6	0	0%
Total	29	100%
G4 and over	0	0%
G5 and over	0	0%

Very Old Buildings		
Damage Grade	Number	Ratio
Grade 0	4	29%
Grade 1	7	50%
Grade 2	0	0%
Grade 3	3	21%
Grade 4	0	0%
Grade 5	0	0%
Grade 6	0	0%
Total	14	100%
G4 and over	0	0%
G5 and over	0	0%

3.3 Building Damage in the Kurokawa Area

Table 4 and Fig.7 show the statistics of 54 buildings and the pictures of the three buildings in the Kurokawa area (see the location in Fig.3). The three buildings (a) – (c) in Fig.7 are located directly above the surface faulting (see their locations in Fig.4(c)). As shown in Table 4, 81%, 9% and 9% of the buildings are wooden, steel and RC buildings, respectively, with less than 4 stories. Among 54 buildings, the number and the ratio of the severely damaged buildings (Damage Grade 4 and over) are 30 and 56%, respectively. There are 11 buildings which are directly above the surface faulting, and 64% of them (7 buildings) are severely damaged. And, there are 43 buildings which are not above the surface faulting, and 53% of them (23 buildings) are severely damaged. Similarly, the ratio (numbers) of the severely damaged buildings for the new, old, and very old buildings are 11% (1), 29% (5), and 81% (17), respectively. On the other hand, those of the severely damaged wooden, steel, and RC buildings are 64% (28), 40% (2), and 0% (0), respectively. Those results together with the extensive ground cracks (see Fig.4(c)) suggest not only the severe strong ground motions, but also the structural weakness of the old wooden houses/apartments.

Fig.7(a) shows an old steel apartment, which is located directly above the surface faulting, and the close up of the foundation damage. The ground deformation destroyed the foundation of unreinforced concrete, and thus, the building structures are tilted and heavily damaged (Damage Grade 4). On the contrary, the RC apartment of 4 stories, which is next to this building (the left in the picture) and out of the fault slip, shows no damage (Damage Grade 0).

Table 4 – Statistical data of the investigated buildings in the Kurokawa area

Structure	Number	Ratio
wooden	44	81%
steel	5	9%
RC	5	9%
Total	54	100%

Story	Number	Ratio
1	12	22%
2	35	65%
3	5	9%
4	2	4%
Total	54	100%

Building Age	Number	Ratio
very old	21	39%
old	23	43%
new	10	19%
Total	54	100%

All Buildings		
Damage Grade	Number	Ratio
Grade 0	7	13%
Grade 1	5	9%
Grade 2	8	15%
Grade 3	4	7%
Grade 4	10	19%
Grade 5	18	33%
Grade 6	2	4%
Total	54	100%
G4 and over	30	56%
G5 and over	20	37%

Buildings on Surace Faulting		
Damage Grade	Number	Ratio
Grade 0	0	0%
Grade 1	2	18%
Grade 2	1	9%
Grade 3	1	9%
Grade 4	5	45%
Grade 5	2	18%
Grade 6	0	0%
Total	11	100%
D4 and over	7	64%
D5 and over	2	18%

Not on Surface Faulting		
Damage Grade	Number	Ratio
Grade 0	7	16%
Grade 1	3	7%
Grade 2	7	16%
Grade 3	3	7%
Grade 4	5	12%
Grade 5	16	37%
Grade 6	2	5%
Total	43	100%
D4 and over	23	53%
D5 and over	18	42%

New Buildings		
Damage Grade	Number	Ratio
Grade 0	5	56%
Grade 1	3	33%
Grade 2	0	0%
Grade 3	0	0%
Grade 4	0	0%
Grade 5	1	11%
Grade 6	0	0%
Total	9	100%
D4 and over	1	11%
D5 and over	1	11%

Old Buildings		
Damage Grade	Number	Ratio
Grade 0	1	0%
Grade 1	28	29%
Grade 2	1	29%
Grade 3	0	12%
Grade 4	0	24%
Grade 5	0	6%
Grade 6	0	0%
Total	30	100%
D4 and over	5	29%
D5 and over	1	6%

Very Old Buildings		
Damage Grade	Number	Ratio
Grade 0	0	0%
Grade 1	1	5%
Grade 2	3	14%
Grade 3	0	0%
Grade 4	7	33%
Grade 5	8	38%
Grade 6	2	10%
Total	21	100%
D4 and over	17	81%
D5 and over	10	48%

Wooden Buildings		
Damage Grade	Number	Ratio
Grade 0	1	2%
Grade 1	4	9%
Grade 2	7	16%
Grade 3	4	9%
Grade 4	9	20%
Grade 5	17	39%
Grade 6	2	5%
Total	44	100%
D4 and over	28	64%
D5 and over	19	43%

Steel Buildings		
Damage Grade	Number	Ratio
Grade 0	1	20%
Grade 1	1	20%
Grade 2	1	20%
Grade 3	0	0%
Grade 4	1	20%
Grade 5	1	20%
Grade 6	0	0%
Total	5	100%
D4 and over	2	40%
D5 and over	1	20%

RC Buildings		
Damage Grade	Number	Ratio
Grade 0	5	100%
Grade 1	0	0%
Grade 2	0	0%
Grade 3	0	0%
Grade 4	0	0%
Grade 5	0	0%
Grade 6	0	0%
Total	5	100%
D4 and over	0	0%
D5 and over	0	0%

Fig.7(b) shows the front and back of an old wooden apartment directly above the surface faulting. Similar to Fig.7(a), the foundation and the building are deformed and heavily damaged due to the ground deformation (Damage Grade 4).

Fig.7(c) shows the collapse of an old wooden apartment above the surface faulting and the close up of the damage (pulling out of a column). This apartment was 3 stories, but the soft first story of the garage in the front completely collapsed by the strong shaking. As shown in the close-up picture, there were no hall-down hardware to fix the columns to the foundation, that caused the overturning of the building (Damage Grade 5).

(a) An old wooden house on the surface fault (Damage grade 4)
(b) A new house on the surface fault (Damage grade 1)
(c) A very old wooden house on the surface fault (Damage grade 4)

Fig. 5 – Building damage on the surface faults in the Takagi area (see the locations of buildings in Fig.2(a))

(a) An old wooden house (left) on the surface fault (Damage grade 3)
(b) A very old wooden house on the surface fault of the front (left: Damage grade 3), and the back (right: a very old warehouse of damage grade 1)

(c) Surface faulting (left) and a very old wooden house on the fault (center and right)

Fig.6 – Building damage on the surface faults in the Shimojin area (see the locations of buildings in Fig.2(b))[10)]

(a) An old steel apartment on the surface fault (Damage grade 4)

(b) An old wooden apartment on the surface fault (Damage grade 4)

(c) An old wooden apartment on the surface Fault (Damage grade 5)

Fig.7 – Building damage on the surface faults in the Kurokawa area (see the locations of buildings in Fig.2(c))

4. Discussion and Summaries

This paper reported the characteristics of the strong ground motion records and the results for investigating building damage near the surface faulting of the 2016 Kumamoto earthquake. The EW components of the strong motions in Mashiki City and Nishihara Village were dominant at longer periods, and showed clearly the fling steps. Those fling steps were caused by the motion of the hanging wall of the normal/right-lateral faulting, and were dominant in the faulting slip direction. The forward directivity pulses, on the contrary, which were dominant in the direction normal to the fault plane (close to the NS components), were not very clear in the records. This is probably due to the complex faulting process and/or the propagation effects of the seismic waves in the local complex media. On the other hand, the EW components of the records in Mashiki City showed the large amplitudes at about 1 sec; they were probably the forward directivity pulses (*i.e.*, reference[7)]).

The results of the building investigation indicated that most of severe damage occurred in those directly above the surface faulting, because of its slip deformation. And, almost all severe damaged buildings were very old wooden houses/apartments, whereas new wooden or RC buildings showed very minor damage. In the Shimojin area, particularly, the ground motion was probably not strong enough to cause severe damage, and thus, the highest damage was Grade 3. All of them were very old wooden buildings and directly above the surface faulting. Those results, namely weak ground motions and the concentration of building damage above the surface faulting, agree with previous studies[11)].

Even though the best counter measure for buildings near active faults is to avoid them, it is unrealistic to prohibit buildings in such areas shown in this study. This is because that it is very difficult to identify the exact locations of the active faults; they differed from those of the actual surface faulting, due to the young alluvial/volcanic sediments and the artificial land development. In addition, the recurrence intervals of the active faults are extremely long (usually several thousand years), as compared with the lifetime of a building. And the most importantly, various safety counter measures are effective, even for the building directly above the surface faulting. For example, the new wooden houses with the mat foundation of RC could prevent the slip deformation from reaching the building, and the combinations of the shear wall and light roofs prevented severe damage (see Fig.5(b)). On the other hand, the old Japanese traditional houses generally suffered severe damage, but their structural flexibilities could prevent collapsing by following the slip deformation (see Fig.5(a),(c), and Fig.6(b),(c)). The collapsed buildings were generally old and lacked both the sufficient earthquake-resisting structural members and the effective connections among them (see Fig.7(c)).

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