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INDOOR DAMAGE AT HIGH-RISE RESIDENTIAL BUILDINGS FROM QUESTIONNAIRE SURVEY AFTER RECENT EARTHQUAKES

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Abstract

In the last decade, Japan has suffered massive earthquakes including the 2011 Tohoku and 2016 Kumamoto earthquakes. Meanwhile, in highly urbanized areas, more than 1300 high-rise residential buildings of over 20 stories have been constructed, some of which have experienced severe shaking during long-period ground motions. Thus, structural engineers have been greatly interested in the types of damage that occur in those high-rises during a massive earthquake. A few buildings are equipped with strong motion observation systems, with records that engineers can use to estimate structural responses and temporal variations of dynamic properties. However, the majority of buildings do not have monitoring systems, thus causing difficulties in evaluating structural responses and/or indoor damage after severe shaking. To clarify what occurred in high-rise residential buildings after the shaking, we employed results from a questionnaire survey for residents on indoor damage.

The questionnaire survey was administered after several damaging earthquakes in Japan and Taiwan, i.e., the 2011 Tohoku (M9.0), the 2016 Kumamoto (M7.0), and the 2018 northern Osaka earthquakes (M6.1) in Japan, and the 2018 Hualien earthquake (M6.4) in Taiwan. In Japan, surveyed buildings were high-rise residential, most reinforced concrete with more than 20 stories. Because in Hualien city, no buildings were over 20 stories, those surveyed were from 10 to 16 stories. Questionnaires were distributed so that we could identify building sites and residents' floors, also including whether they were in or out of their apartments. The survey covered a wide range of questions, e.g., seismic intensity felt during the main shock, action difficulty, movement and/or overturning of furniture, and cracks in interior materials, such as wallpaper. Most survey items were ranked on a five-point scale, and all crosstab charts were made by roughly dividing floors into three groups, i.e., upper, middle, and lower floors.

Floor responses expressed by moving and/or overturning of furniture became large as the floor level increased, regardless of type of earthquake and construction site. In contrast, wallpaper cracks were concentrated in lower floors in buildings in the Tokyo metropolitan area during the 2011 Tohoku earthquake. The damage index for wallpaper cracks on middle floors also became large for the other three earthquakes because high-rise buildings' structural responses to pulse-like ground motions differed slightly from those for long-period ground motions with long duration. In the 2018 Hualien earthquake, indoor damage indices among three groups of buildings differed, even though the distance from the Milun fault was almost the same, probably due to site amplification characteristics.

Keywords: high-rise residential building, questionnaire survey, indoor damage, overturning of furniture, wallpaper crack

1. Introduction

In Japan, more than 1300 high-rise residential buildings of 20 stories or more have been constructed, and their sites are plotted in Fig. 1. Most are located in densely populated areas like Tokyo and Osaka, but recently, such construction has spread to other areas' medium-sized cities, for instance, to prefectural capitals.

Within the recent past, Japan has experienced a number of huge earthquakes. During mega-thrust earthquakes, such as the 2011 Tohoku earthquake (Mw9.0), long-period ground motions of long duration were observed over a wide area [1]. During inland crustal earthquakes, such as the 1995 Kobe earthquake (Mw6.9) and the 2016 Kumamoto earthquake (Mw7.0), pulse-like ground motions were recorded near the epicenters.

During the 2011 Tohoku earthquake, ground motions of large amplitude and long duration were observed in the Kanto region, including in the Tokyo metropolitan area. A large number of high-rise residential buildings in the Kanto region shook severely. Quite a few buildings manifested nonlinear behavior, observed through strong motion records obtained from several floors (at least, the topmost and first floors) equipped with sensors [2].

Due to high-rise structures' fierce shaking during the main shock and aftershocks, furniture fell over, small items fell or were scattered, and many people were forced to live inconveniently due to interruption of elevator and lifeline operations. Although long-period seismic motion's impact on high-rise residential buildings' living environment is critical for residents, little is known about direct physical damage, including indoor damage, for example, furniture moved or overturned, cracks in wallpaper and concrete walls—along with human damage like anxiety and behavioral difficulties.

In this paper, we summarize results of a questionnaire survey for residents of high-rise residential buildings on indoor damage during four severe earthquakes. According to survey results, we discuss differences in damage depending on type of earthquake, type of structure, and construction region.

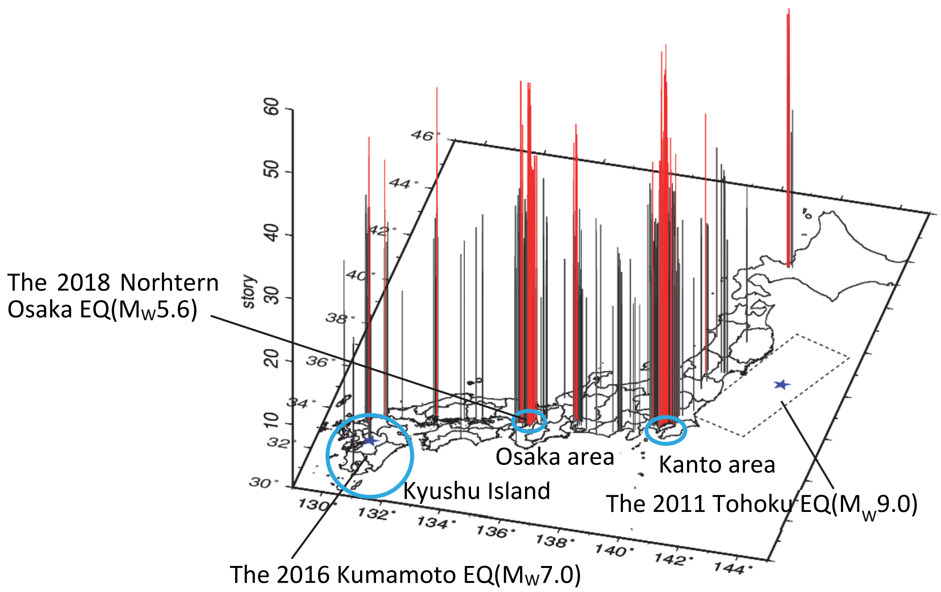


Fig. 1 – Location of high-rise residential buildings in Japan with more than 20 stories. Red bars indicate those with more than 40 stories.

2. Questionnaire survey

2.1 Earthquakes and buildings surveyed

The earthquakes surveyed were the 2011 Tohoku earthquake (Mw9.0), and three inland crustal earthquakes, the 2016 Kumamoto (Mw7.0), the 2018 northern Osaka (Mw5.6), and the 2018 Hualien in Taiwan (Mw6.4).

Table 1 summarizes the surveyed buildings, which in Japan are high-rise residential buildings, most reinforced concrete (RC) with more than 20 stories. Because Hualien city has no buildings of over 20 stories, those are from 10 to 16 stories. Numbers of surveyed buildings were 36 after the 2011 Tohoku earthquake [3], 10 after the 2016 Kumamoto earthquake [4], eight after the 2018 northern Osaka earthquake [5], and nine after the 2018 Hualien earthquake [6]. The total of buildings was 63, including duplicates, and Fig. 2 plots their locations. Most are moment-resisting RC structures. Seismically isolated and controlled structures are included, which enable us to discuss differences in indoor damage between those and conventional earthquake-resistant structures.

In Japan, questionnaires were posted to residents, and responses were collected using enclosed return envelopes. In some buildings, questionnaires were distributed by inserting them into residents' periodically distributed journals. For the 2018 Hualien earthquake in Taiwan, we distributed questionnaires to residents through each building's janitor, who also collected the completed surveys. We took response forms home for tabulation and analysis.

Table 1 lists the number of questionnaires collected for each building, an overall total of more than 3600 valid responses. Of course, the number of responses varied depending on the number of each building's residential units. After the 2011 Tohoku earthquake, the response rate was about 20%. For the 2016 Kumamoto earthquake, the response rate was almost 50% for buildings in Kumamoto City, because the survey was conducted a month after the earthquake and there was a great deal of interest. Questionnaires were distributed so we could identify residents' building sites and floors.

2.2 Content of the questionnaire

The questionnaire covered the following:

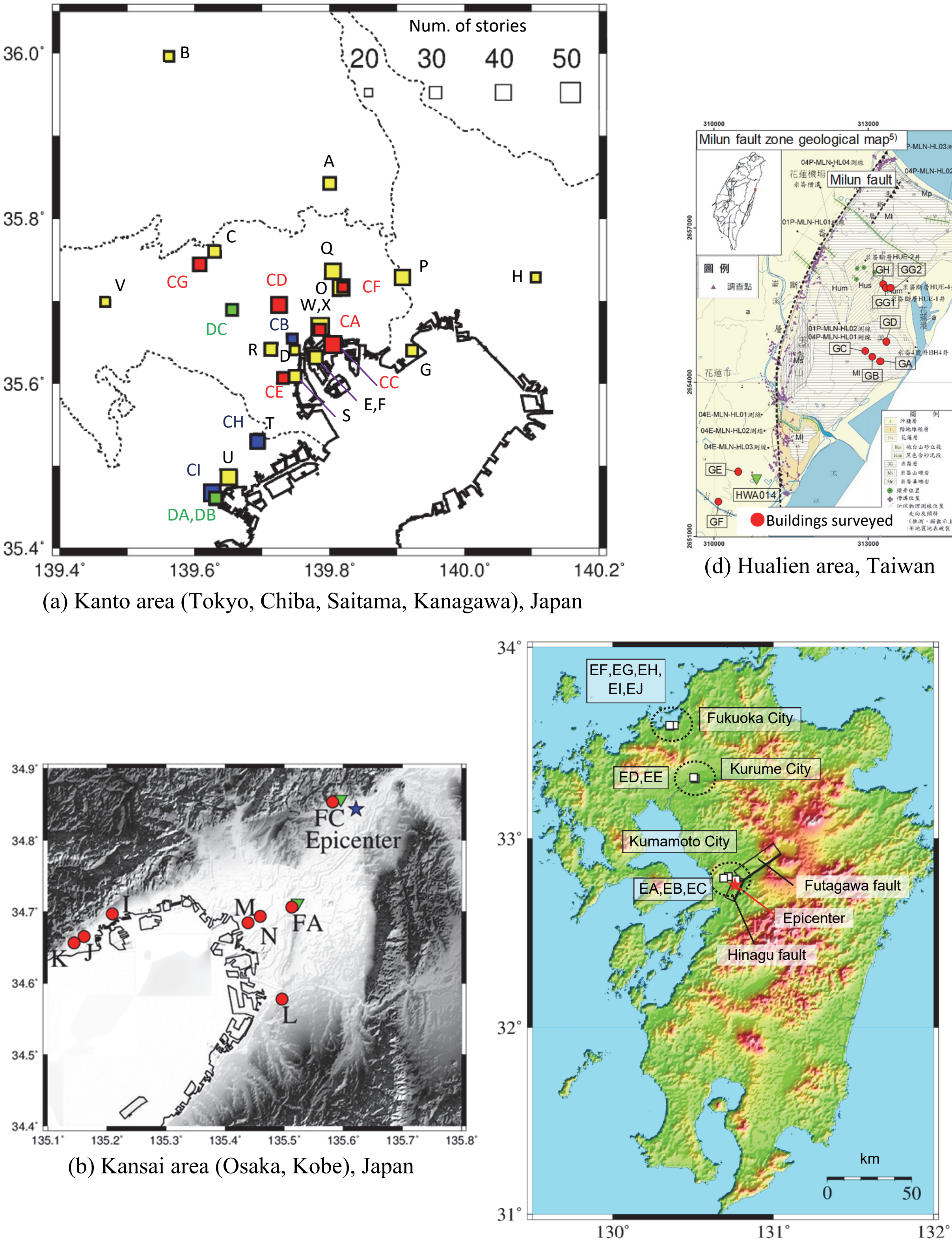
- ✓ Residents' floor number (for cross-tab data analysis)
- ✓ Residents' location—in or out of their apartments
- ✓ Seismic intensity scale during the main shock
- ✓ Residents' difficulties in performing actions ("action difficulty") during massive shaking
- ✓ Residents' development of insecurity as a psychological condition
- ✓ Moved and/or overturned furniture (e.g., drawers, refrigerators)
- ✓ Small items scattered
- ✓ Cracks in interior materials, such as wallpaper.

Most survey items were ranked according to a five-point scale. As examples, answers for action difficulty, overturning of furniture, and cracks in wallpaper are listed in Tables 2 and 3. The questionnaire also included some open-ended questions, for instance, special comments on floor shaking and indoor damage, anxiety about the future, and injuries, if any, during massive shaking. In addition, we asked questions about conditions of lifeline utilities, for example, elevators, water supply, electricity, and gas—and about the need for an earthquake early warning system. For each area, aggregates were compiled.

Table 1–Buildings under study and number of questionnaires collected

Earthquake	BLDG. code	Site	Main structure	Stories	No. of respondents	Remarks
2011 Tohoku	A	Saitama	RC	30	72	
	B	Saitama	RC	25	25	
	C	Tokyo	RC	30	25	
	D	Tokyo	RC	24	30	
	E	Tokyo	RC	32	53	
	F	Tokyo	RC	33	27	
	G	Chiba	RC	28	31	
	H	Chiba	RC	24	18	
	I	Hyogo	RC	33	20	
	J	Hyogo	RC	36	24	
	K	Hyogo	SRC	25	22	
	L	Osaka	RC	43	69	
	M	Osaka	CFT	40	37	
	N	Osaka	RC	31	27	
	O	Tokyo	RC	41	67	
	P	Tokyo	RC	37	67	
	Q	Tokyo	RC	38	61	
	R	Tokyo	RC	32	73	
	S	Tokyo	RC	30	82	
	T	Tokyo	RC	35	51	
	U	Kanagawa	CFT	40	66	
	V	Kanagawa	RC	24	58	
	W	Tokyo	SRC	37	89	
	X	Tokyo	RC	43	114	
	CA	Tokyo	RC	29	30	
	CB	Tokyo	RC	25	11	Controlled
	CC	Tokyo	RC	42	46	
	CD	Tokyo	RC	38	68	
	CE	Tokyo	RC	28	26	Isolated
	CF	Tokyo	RC	26	32	
	CG	Tokyo	RC	33	51	
	CH	Kanagawa	RC	34	66	Controlled
	CI	Kanagawa	RC	41	85	Controlled
	DA	Kanagawa	RC	30	265	Isolated
	DB	Kanagawa	RC	30	147	Isolated
	DC	Tokyo	RC	28	103	Isolated
2016 Kumamoto	EA	Kumamoto	SRC	20	56	
	EB	Kumamoto	RC	25	60	
	EC	Kumamoto	RC	36	109	Controlled
	ED	Kurume	RC	19	63	
	EE	Kurume	RC	35	27	Isolated
	EF	Fukuoka	RC	20	43	
	EG	Fukuoka	RC	27	86	
	EH	Fukuoka	RC	29	33	Controlled
	EI	Fukuoka	RC	30	35	Isolated
	EJ	Fukuoka	RC	29	24	Controlled
2018 Northern Osaka	I	Hyogo	RC	33	73	
	J	Hyogo	RC	36	79	
	K	Hyogo	SRC	25	81	
	L	Osaka	RC	43	130	
	M	Osaka	CFT	40	97	
	N	Osaka	RC	31	83	
	FA	Osaka	RC	28	93	
	FC	Osaka	RC	20	28	
2018 Hualien	GA	Hualien	RC	12	21	
	GB	Hualien	RC	13	22	
	GC	Hualien	RC	10	42	
	GD	Hualien	RC	11	41	
	GE	Hualien	RC	13	46	
	GF	Hualien	RC	16	66	
	GG-1	Hualien	RC	14	31	
	GG-2	Hualien	RC	14	30	
	GH	Hualien	RC	13	29	

The number of buildings is 63, including duplicates.
The number of valid responses was 3,666.
“Controlled” indicates buildings with passive seismic control devices.
“Isolated” indicates seismically isolated buildings.



(a) Kanto area (Tokyo, Chiba, Saitama, Kanagawa), Japan

(d) Hualien area, Taiwan

(b) Kansai area (Osaka, Kobe), Japan

(c) Kyushu area (Kumamoto, Fukuoka), Japan

Fig. 2 – Sites of high-rise residential buildings listed in Table 1

Table 2 Responses for “Action difficulty” and “Cracks in wallpaper” and their corresponding scores.

Type of answers	Action difficulty	Cracks in wallpaper	Scores
Ⅴ	Impossible to act	Severely cracked	4
Ⅳ	↑ Intermediate level ↓	↑ Intermediate level ↓	3
Ⅲ	Unstable but possible to act	Partially cracked	2
Ⅱ	↑ Intermediate level ↓	↑ Intermediate level ↓	1
Ⅰ	Possible to act	No cracks	0

Table 3 Responses for “Moving and/or overturning of furniture” and corresponding scores.

Type of answers	Moving and/or overturning of furniture	Scores
Ⅴ	Severely moved and/or overturned	0.8
Ⅳ	↑ Intermediate level ↓	0.6
Ⅲ	Partially moved and/or overturned	0.4
Ⅱ	↑ Intermediate level ↓	0.2
Ⅰ	No moving	0

3. Outline of questionnaire results

3.1 Variation of height-wise trend depending on type of earthquake

Questionnaire results for movement and/or overturning of furniture and home appliances and for cracks in wallpaper were compiled for each region. Surveyed buildings were A–V in the Kanto region in Fig. 2(a) during the 2011 Tohoku earthquake; EA–EC in Kumamoto City in Fig. 2(c) during the 2016 Kumamoto earthquake; and GA–GH in Fig. 2(d) during the 2018 Hualien earthquake in Taiwan. All crosstab charts were constructed by dividing building floors into roughly three groups, that is, upper, middle, and lower.

The moving and/or overturning of furniture in Fig. 3 commonly increased from lower to upper floors for any earthquake. Although not shown here, the same trend was observed for seismic intensity felt during the main shock and for action difficulty.

During the 2011 Tohoku earthquake, however, cracks in the wallpaper (Fig. 4) were the most serious on lower floors. During the 2016 Kumamoto and 2018 Hualien earthquakes, cracks in the wallpaper were concentrated not only on lower but also on middle floors. During inland crustal earthquakes, nearby buildings are subjected to pulse-like ground motions with a predominant period of 1 to 3 seconds, resulting in large inter-story drift in middle and/or upper stories.

3.2 Spatial variation of indoor damage in the Tokyo metropolitan area during the 2011 Tohoku earthquake

In the Tokyo metropolitan area during the 2011 Tohoku earthquake, strong motion records indicate that the long-period component affecting high-rise buildings’ responses was greater in the Tokyo Bay area than in the inland area [2]. Interior cracks were the largest on lower floors (Fig. 4). Spatial distribution of cracks in the wallpaper on lower floors is plotted in Fig. 5 for buildings A to V in Fig. 2(a). An index of cracks in wallpaper was evaluated by averaging scores in Table 2. The color-filled circles in Fig. 5 are peak values of ${}_{P}S_{V}$ (h=5%) in a period ranging from 1.5s to 3.5s of observed ground motions, denoted as ${}_{P}S_{V}(1.5–3.5)$.

Values for buildings in the Tokyo Bay area from Urayasu to Yokohama are clearly larger than those for inland buildings. This trend is the same as distribution of ${}_{P}S_{V}(1.5–3.5)$ of strong motion records. The spatial distribution of long-period ground motions in and around the Tokyo Bay area during the 2011 Tohoku earthquake was highly variable, perhaps due to differences in the shallow subsurface structure including nonlinear behavior.

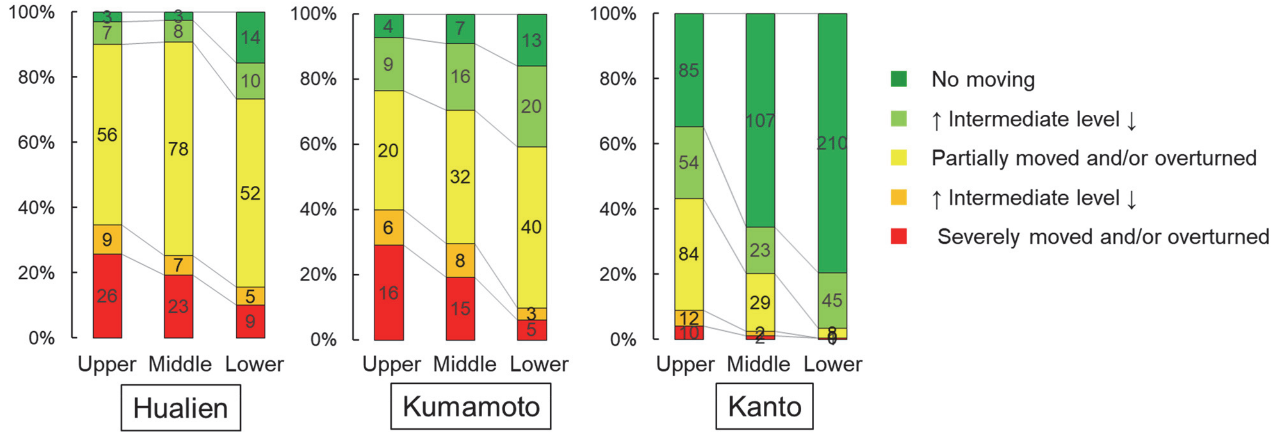


Fig. 3 – Moving and/or overturning of furniture during three major earthquakes.

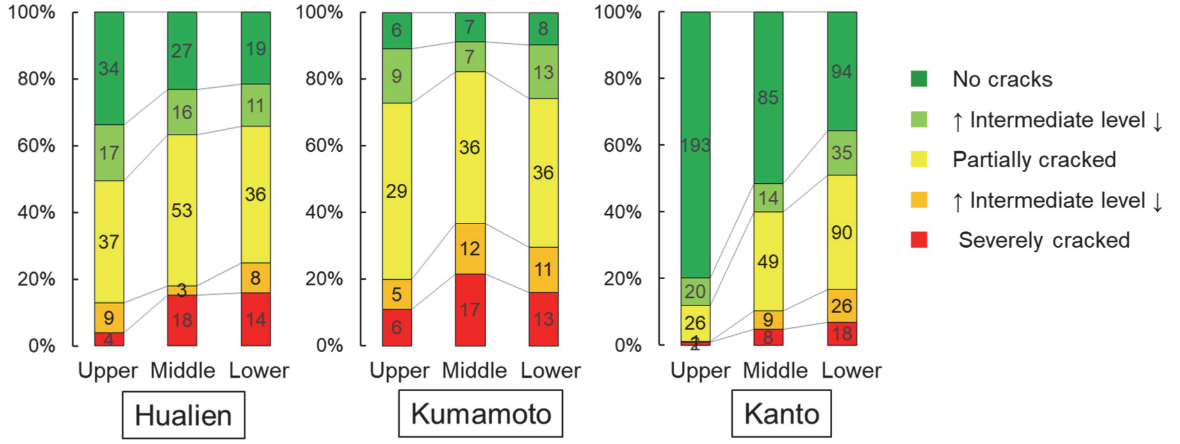


Fig. 4 – Cracks in wallpaper during three major earthquakes.

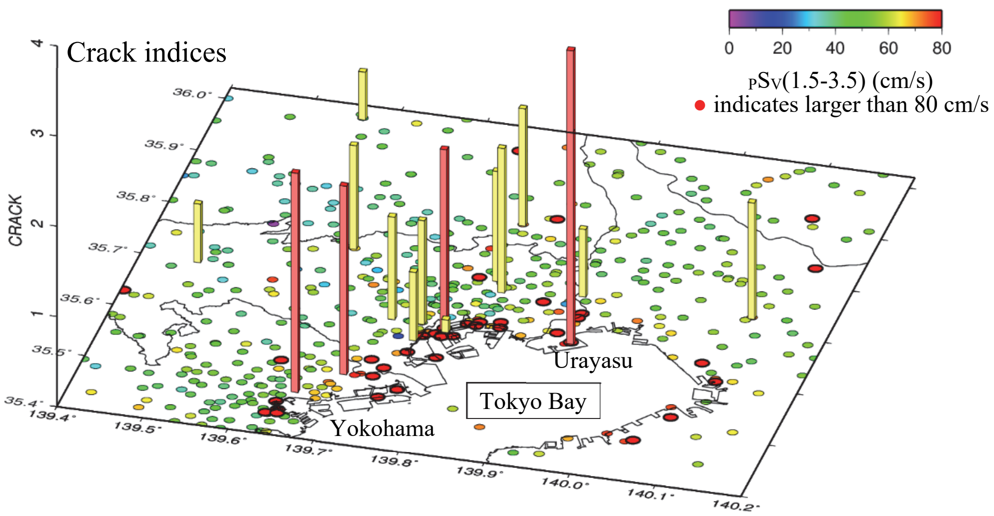


Fig. 5 – Spatial distribution of indices for crack in wallpaper on the lower floors of high-rise residential buildings, A-V, in the Tokyo metropolitan area during the 2011 Tohoku earthquake. Red bars indicate those larger than 1.8. Colored circles are peak values of $_{P}S_{V}$ (h=5%) in period range between 1.5s and 3.5s, $_{P}S_{V}$(1.5–3.5), of observed ground motions.

3.3 Differences between earthquake-resistant, seismically controlled, and seismically isolated buildings

In addition to earthquake-resistant structures, in recent years, the number of high-rise residential buildings equipped with seismic control devices or seismic isolation has increased. Reports state that seismically isolated buildings suffered less interior damage during the 2011 Tohoku earthquake. We conducted a questionnaire survey with residents of high-rise residential buildings with seismic control and seismic isolation systems, and examined indoor damage caused by the 2011 Tohoku earthquake, focusing on differences in structural types and studying buildings CA–CI and DA–DC in Fig. 2. Some buildings use low yield steel as seismic control devices.

Figs. 6 and 7 compare the moving and/or overturning of furniture and cracks in wallpaper, respectively. The height-wise trend of these two indoor damage types is the same as those in Figs. 3 and 4. Indeed, the amount of indoor damage decreased in the order of seismic resistance, seismic control, and seismic isolation. Especially in seismically isolated buildings, more than 90% of respondents answered that nothing had moved at all, unlike in seismic resistant and seismically controlled buildings. To some extent, however, seismically controlled buildings also contributed to reduced indoor damage.

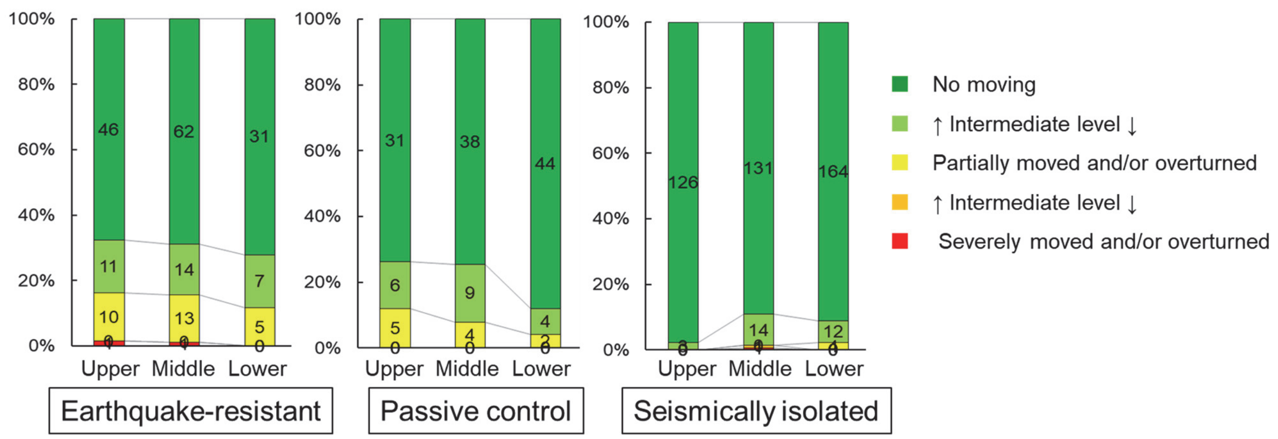


Fig. 6 – Moving and/or overturning of furniture for three types of buildings.

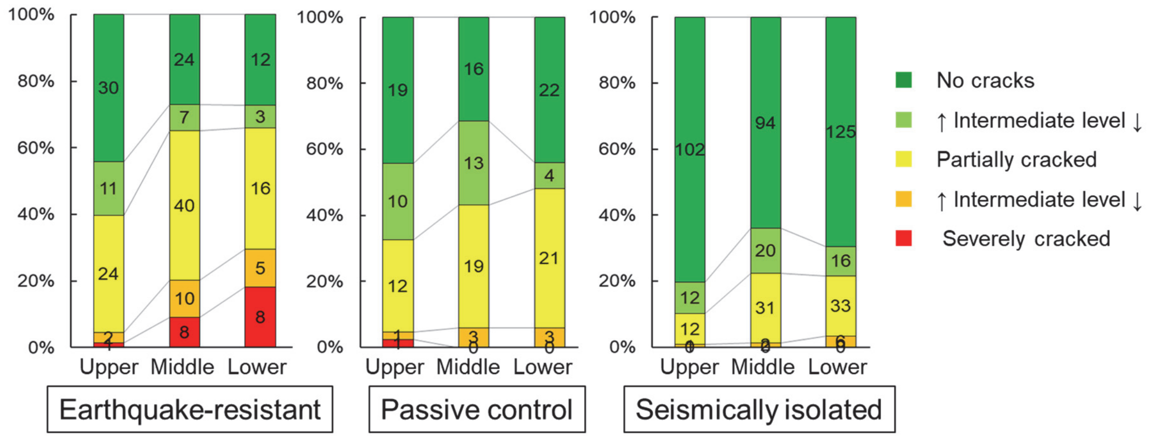


Fig. 7 – Cracks in wallpaper for three types of buildings.

3.4 Regional variation of indoor damage near the seismic fault during the 2018 Hualien earthquake

The buildings in Hualien city in Fig. 2(d) are all located in the Milun fault's vicinity. Among these buildings, results were tabulated by region, with the Milun fault's west side as the southwest region (two buildings, GE & GF), the fault's east side as the central region (four buildings, GA–GD), and the northeast region (three buildings, GG-1, GG-2, & GH).

Results for cracks in wallpaper are compared in Fig. 8. Indoor damage indices among the three groups of buildings differed, even though the distance from the Milun fault is almost the same, attributed to site amplification characteristics. In general, indoor damage was prominent in northeast region buildings. Additionally in the northeast region, many cracks were observed on exterior walls of building GH's low-rise portion in Fig. 9. We confirmed that many cracks were repaired on exterior walls when we conducted on-site microtremor measurement.

Although no strong ground motion was recorded in the northeast region during the 2018 Hualien earthquake, presumably, earthquake motion that caused cracks in interior materials did occur in this area.

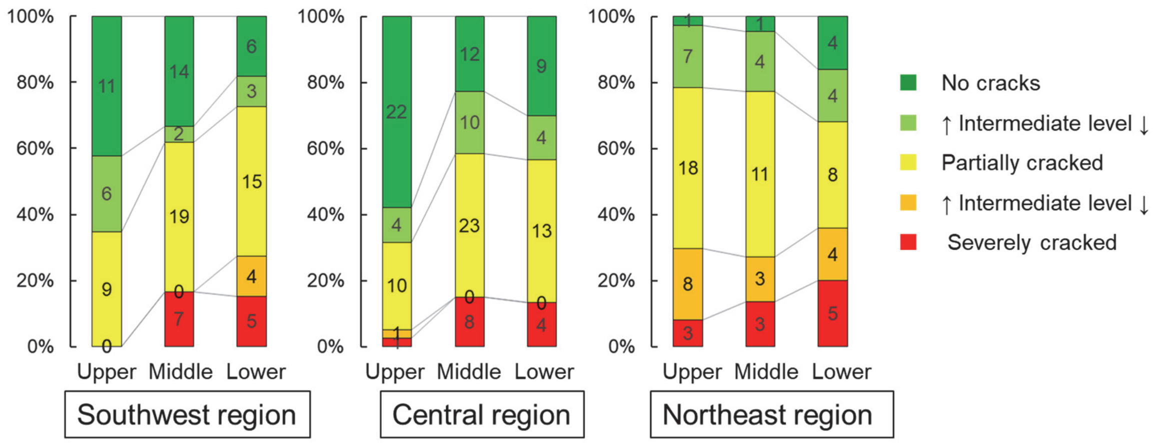


Fig. 8 – Cracks in wallpaper during the 2018 Hualien earthquake.

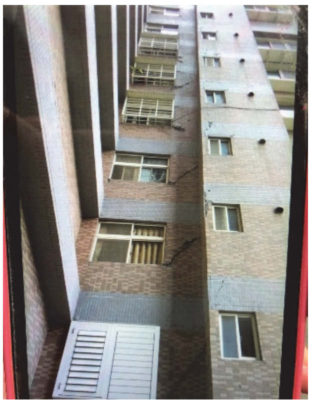


Fig. 9 – Cracks in exterior walls of the low-rise part of the building GH.

4. Summary and discussion

This paper summarized survey results for high-rise buildings' residents on indoor damage during four severe earthquakes. Results were compiled by dividing floors into roughly three groups: upper, middle, and lower. The number of buildings surveyed was 63, including duplicates, and valid responses numbered more than 3600.

Differences in indoor damage were discussed according to type of earthquake, type of structure, and construction region.

In a few high-rise residential buildings, strong motion seismographs are installed. But even where ground motion records are not available, a questionnaire survey on indoor damage enables us to discuss differences in earthquake motion input in neighboring areas and the effect of seismic response reduction by seismically controlled and seismically isolated buildings. The questionnaire survey requires much time and effort for its preparation and distribution, a large amount of work to tabulate responses, and costs associated with printing and mailing. Nevertheless, the survey has a great advantage in that it allows us to listen directly to occupants' voices after an earthquake. Although not described in this paper, the questionnaire also included a survey on lifelines after earthquakes, including operation of elevators and supplies of water, electricity, gas, and others, providing data valuable for the evaluation of life continuity planning and resilience performance in high-rise residential buildings.

Acknowledgments

We would like to express our sincere gratitude to the residents of the high-rise residential buildings who responded to our questionnaire survey for their cooperation. This survey research was conducted in collaboration with our colleagues: Prof. Takenori Hida, Dr. Kento Suzuki, Prof. Wang Xin, and graduates of Nagano Laboratory, Tokyo University of Science since 2011. The questionnaire survey for the 2018 earthquake in northern Osaka was conducted in collaboration with the Japan Meteorological Agency; the survey for the 2018 earthquake in Hualien, Taiwan was conducted in collaboration with National Dong Hwa University, Taiwan. We used Generic Mapping Tools [7] for some figures.

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