17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

DAMAGE ASSESSMENT ACTIVITIES OF SCHOOL BUILDINGS AFTER RECENT MAJOR EARTHQUAKES IN JAPAN

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Abstract

Japan is located in an earthquake-prone region and has been repeatedly exposed to damaging earthquakes. When a damaging earthquake occurs, the earthquake engineering community has been investigating damage to structures and affected areas. To restore an earthquake-damage community as quickly as possible, a well-prepared reconstruction strategy is most essential. When an earthquake strikes buildings and destructive damage occurs, damage assessments should be promptly performed, and then technically and economically sound solutions need to be applied to the buildings, if rehabilitation is needed. To this end, quantitative post-earthquake damage assessment is often made to identify their damage and residual seismic capacity in detail, where a well-organized system for post-earthquake damage assessment is needed especially when a large number of buildings are affected.

The Architectural Institute of Japan (AIJ) has been greatly contributing to the post-earthquake damage assessment and restoring activities of school facilities after major damaging earthquakes in Japan, in close cooperation and coordination with the Ministry of Education, Culture, Sports, Science and Technology (MEXT). Immediately after a major damaging earthquake, AIJ set up a special committee on “Seismic Capacity of School Buildings” in cooperation with MEXT. After the chief investigator and secretaries were assigned, they invited committee members from university professors and researchers to form field investigation teams. The objectives of the investigations are primarily to:

(1) Describe and record damage through careful and detailed field surveys.
(2) Highlight typical damage pattern in both structural and non-structural aspects.
(3) Identify main cause of observed damage with respect to structural planning, seismic code, design/redesign and construction practices etc.
(4) Demonstrate the effectiveness of seismic rehabilitation.
(5) Rate building damage in accordance with judgement criteria.
(6) Find the relationship between seismic capacity and damage.
(7) Identify unrecoverable buildings and propose their demolition and reconstruction.
(8) Instruct rehabilitation and redesign of damaged but recoverable buildings, etc.

In the last quarter century, this activity was first made after the Kobe earthquake in 1995 and successively after the Niigata-ken Chuetsu earthquake in 2004, the Great East Japan (Tohoku) earthquake in 2011, and the Kumamoto earthquake in 2016.

This paper briefly reviews damage primarily to reinforced concrete school buildings due to recent four major damaging earthquakes in Japan and damage assessment activities, which were directed by AIJ special committee members to help local governments and engineers judge necessary actions to be taken for damaged school buildings. The general flow and criteria for assessment, findings to discuss the seismic performance required in buildings, and lessons learned and re-learned through these activities and efforts that should be implemented to further mitigate damage and to develop resilient society are also discussed.

Keywords: reinforced concrete; school buildings; post-earthquake damage assessment; seismic rehabilitation; residual seismic capacity ratio index R

1. Introduction

To restore an earthquake-damage community as quickly as possible, a well-prepared reconstruction strategy is most essential. When an earthquake strikes buildings and destructive damage occurs, damage assessments should be promptly performed, and then technically and economically sound solutions need to be applied to the buildings, if rehabilitation is needed. To this end, quantitative post-earthquake damage assessment is often made to identify their damage and residual seismic capacity in detail, where a well-organized system for post-earthquake damage assessment is needed especially when a large number of buildings are affected.

During the last quarter century in Japan, especially after the 1995 Kobe earthquake that hardest hit the urban center of Kobe city, the Architectural Institute of Japan (AIJ) has been greatly contributing to the post-earthquake damage assessment activities of school buildings after major damaging earthquakes, in close cooperation and coordination with the Ministry of Education, Culture, Sports, Science and Technology (MEXT). Immediately after a major damaging earthquake, AIJ set up a special committee on "Seismic Capacity of School Buildings" in cooperation with MEXT. This activity first started after the Kobe earthquake in 1995, followed by three activities after the Niigata-ken Chuetsu earthquake in 2004, the Great East Japan (Tohoku) earthquake in 2011, and the Kumamoto earthquake in 2016. The main objectives of the investigations are (1) to rate building damage to recommend local governments in charge of school management whether the building should be "rehabilitated and reused" or "demolished and reconstructed" and (2) to help them redesign and rehabilitate the damaged building through providing technical guides, as well as (3) to investigate the root cause of damage and (4) to scientifically describe and record the damage.

This paper briefly describes experiences and lessons learned from these damage assessment activities of school buildings after major earthquakes in Japan, emphasizing (1) the general flow and criteria for assessment and (2) findings to discuss the seismic performance required in buildings, which will be useful for efficient damage assessment after the huge Nankai Trough earthquake expected in near future.

2. Typical Damage to School Buildings from Recent Four Major Earthquakes in Japan

After major damaging earthquakes, investigations of school buildings have been often made extensively in Japan. School buildings, especially public school buildings, may have advantage in surveys over other buildings because their structural system is generally simpler than other commercial or large scale buildings, and they can serve as best examples to learn fundamental but essential lessons to be implemented in the future structural design. **Fig. 1** and **Table 1** shows general information of damage from four major damaging earthquakes after which the systematic damage assessment activities of school buildings were made.

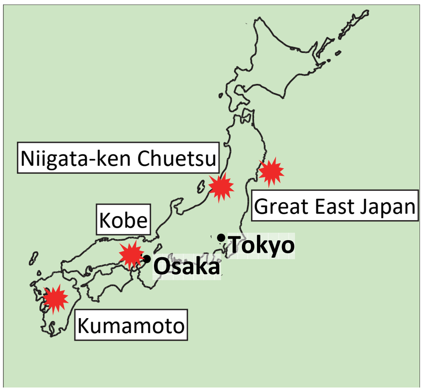

Fig. 1: Four major earthquakes

Table 1: Damage statistics of four major damaging earthquakes in Japan [1]

Earthquake	Magnitude	Casualties		Damaged Houses		Remark
		Death Toll	Injured	Collapse	Major damage	(as of)
1995 Kobe	7.3	6,437*	43,792	104,906	144,274	5/19/2006
2004 Niigata-ken Chuetsu	6.8	68	4,805	3,175	13,801	9/24/2008
2011 Great East Japan (Tohoku)	9.0	18,880*	6107	129,914	258,591	5/30/2012
2016 Kumamoto	7.3	228	2,753	8,697	34,037	4/13/2017

* The number includes missing persons.

2.1 Kobe earthquake in 1995

The 1995 Kobe earthquake, which centered the urban area of Hanshin-Awaji district, caused extensive structural and/or non-structural damage to approximately 4,500 educational facilities. No fatalities fortunately resulted from damaged schools since the quake struck the area early in the morning. Some school buildings, however, sustained serious damage as shown in **Photo 1**, and 54 buildings were demolished and reconstructed following the event. The Government of Japan (GOJ) appropriated 94 billion JPY for fiscal years 1994 and 1995 to restore damaged educational facilities and subsidized 1,126 buildings [2, 3]. As will

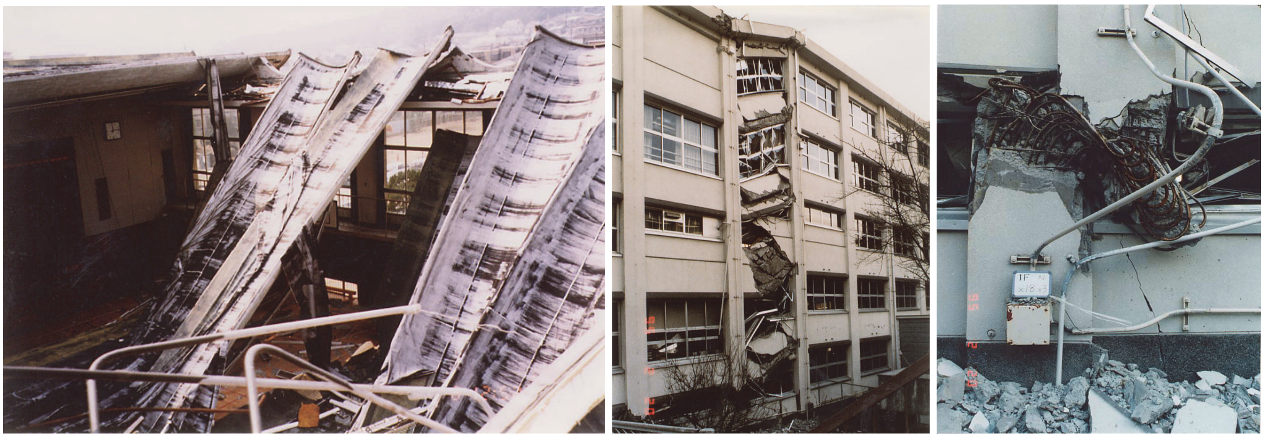

Photo 1: Serious damage to school buildings (1995 Kobe earthquake) [4]

Photo 2: Structural and non-structural damage to school buildings (2004 Niigata-ken Chuetsu earthquake) [5]

be discussed later, older buildings designed under the pre-1981 seismic code were clearly recognized potentially vulnerable and a nationwide seismic evaluation and rehabilitation program started after this event.

2.2 Niigata-ken Chuetsu earthquake in 2004

This earthquake was a localized event but caused extensive damage to buildings as shown in **Photo 2**. After 1995 Kobe earthquake, the seismic rehabilitation program was implemented throughout Japan and this event was the first major earthquake to demonstrate the effectiveness of seismic rehabilitation under severe earthquake ground motions. The observed damage clearly demonstrated that the rehabilitated school buildings performed successfully and the effectiveness of seismic rehabilitation was re-recognized. This earthquake was followed by numbers of aftershocks, and they caused remarkable damage to non-structural elements such as light shades or interior walls, which might harm evacuees as shown in the photo, and the inspection of damaged buildings to rapidly evaluate their safety to aftershocks was highlighted.

2.3 Great East Japan (Tohoku) earthquake in 2011

The Great East Japan (Tohoku) earthquake was one of the most damaging earthquakes in the modern history of Japan. Massive and widespread damage was found in coastal areas due to devastating tsunamis, but as was found in Niigata-ken Chuetsu earthquake, seismically rehabilitated buildings generally performed well while old and vulnerable buildings left not upgraded had most serious damage, including total or partial collapse as shown in **Photo 3**. It should also be reminded that ceilings of theater/concert halls or gymnasiums which fell down to the audience area or indoor playground caused critical damage with fatalities. Due to such damage observed, the MEXT issued a notice to accelerate the countermeasures to eliminate falling hazard as well as further implementation of structural rehabilitation.

Photo 3: Ground shaking and tsunami damage to school buildings (2011 Great East Japan earthquake) [6]

2.4 Kumamoto earthquake in 2016

Two major shakings with the main shock following a foreshock that occurred 28 hours earlier consecutively hit Kumamoto and Oita areas, resulting in extensive damage to structures, especially to timber houses. As was found in the past major earthquakes, this event also caused remarkable damage to school buildings which were not seismically upgraded before the events, while those upgraded performed well. It should be noted, however, that some buildings designed highly dependent on ductility with lateral resistance reduction largely responded, causing large residual deformations. **Photo 4** shows a contrasting performance, one showing no damage after seismic rehabilitation and the other large residual deformations in columns.

3. Post-earthquake Damage Assessment System after Major Earthquakes in Japan

Once a damaging earthquake occurs, various research institutes, organizations, and individuals launches field investigations of affected areas. To restore earthquake damaged buildings as quickly as possible, a well-organized system for damage survey and restoration is most needed for a resilient society.

The AIJ has been greatly contributing to the post-earthquake damage assessment and restoring activities of school facilities after major damaging earthquakes in Japan, in close cooperation and coordination with MEXT. Immediately after a major damaging earthquake, AIJ set up a special committee on "Seismic Capacity of School Buildings" in cooperation with MEXT. After the chief investigator and secretaries were assigned, they invited committee members from university professors and researchers to form field investigation teams. The objectives of the investigations are primarily to:
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(5) Rate building damage in accordance with judgement criteria.
(6) Find the relationship between seismic capacity and damage.
(7) Identify unrecoverable buildings and propose their demolition and reconstruction.
(8) Instruct rehabilitation and redesign of damaged but recoverable buildings, etc.

In the last quarter century, this activity was first made after the Kobe earthquake in 1995, and successively after the Niigata-ken Chuetsu earthquake in 2004, the Great East Japan (Tohoku) earthquake in 2011, and the Kumamoto earthquake in 2016. **Table 2** shows the statistics of buildings investigated after these four earthquakes [4 - 7].

Photo 4: Survived and severly damaged school buildings (2016 Kumamoto earthquake) [7]

Table 2: Key information of school buildings investigated after four major earthquakes in Japan [4 - 7]

Earthquake	Number of Surveyed Prefectures	Investigated Schools	Investigated Buildings*1	Committee Members	Investigation Period
1995 Kobe	1	139	272*2	38	1 month
2004 Niigata-ken Chuetsu	1	46	147	20	2 weeks
2011 Great East Japan (Tohoku)	7	414	778	64	2 months
2016 Kumamoto	2	---	518	53	2 months

*1 The number of investigated buildings includes RC, steel, and timber school buildings and gymnasium facilities.
*2 The number increases to approximately 800 buildings including those only with exterior building surveys.

4. Damage Rating Criteria

In the past four events, the damage of extensive number of school building needed to be rated, and the two-tiered assessment procedure was employed. This procedure is provided respectively for reinforced concrete (RC), steel, timber school buildings. Although the detailed criteria for damage rating differ depending on the structural type, each structural type shares the basic policy for rating. **Fig. 2** shows the general flow of the damage raging procedure for RC school buildings [after 7].

The Tier-1 damage rating is designed to quickly identify obviously unrecoverable buildings through visual inspection and/or simple measurement. When the Tier-1 rates the building unrecoverable, it will be renewed after demolition and reconstruction. The criteria to find unrecoverable buildings are:
1) Obviously dangerous condition to enter due to extensive damage to major structural columns, walls, or beams, causing total or partial collapse,
2) Foundation settlement with more than 1m (0.2m for pile foundation),
3) Foundation tilting with more than 6/100 rad. (3/100 rad. for pile foundation), or
4) Class V[1] damage to more than 35% of surveyed columns and walls.

The Tier-2 damage rating then applies to those which are not obviously identified unrecoverable in Tier-1. In this rating, the Guidelines for Post-earthquake Damage Evaluation and Rehabilitation [8] applies, where damage rating of a building is performed on foundation system and superstructure system, respectively and the damage rating is made in a combination form for each system such as "no damage in foundation and moderate damage in superstructure." The Guidelines also provides required actions depending on the damage, the estimated residual seismic capacity, and earthquake intensity at the building site. The general procedure can be briefly described as follows and the detailed procedure can be found in reference [9].

(1) Damage rating of foundation and superstructure:
   (a) The damage to foundation is rated from the matrix of tilting angle of overall structure and foundation settlement.
   (b) The damage to each structural member is inspected and classified into one of the classes I through V. The residual seismic capacity ratio index *R*, which is defined as the ratio of capacity of post-damaged to that of pre-damaged condition (i.e., the ratio of the residual capacity to the original), is calculated and the overall damage rating of the building is performed base on the *R*-index.

(2) Determination of rehabilitation actions:
   Based on the damage rate made in (1) above and the intensity of shaking experienced at the building site, necessary rehabilitation actions such as repair or strengthening are determined.

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[1] The following criteria apply to identify Damage Class V in the Tier-1 procedure:
   (1) Lateral drift of columns $\geq$ 1/100,
   (2) Axial deformation in columns $\geq$ 0.5/100, or
   (3) Lateral drift in walls $\geq$ 0.5/100.

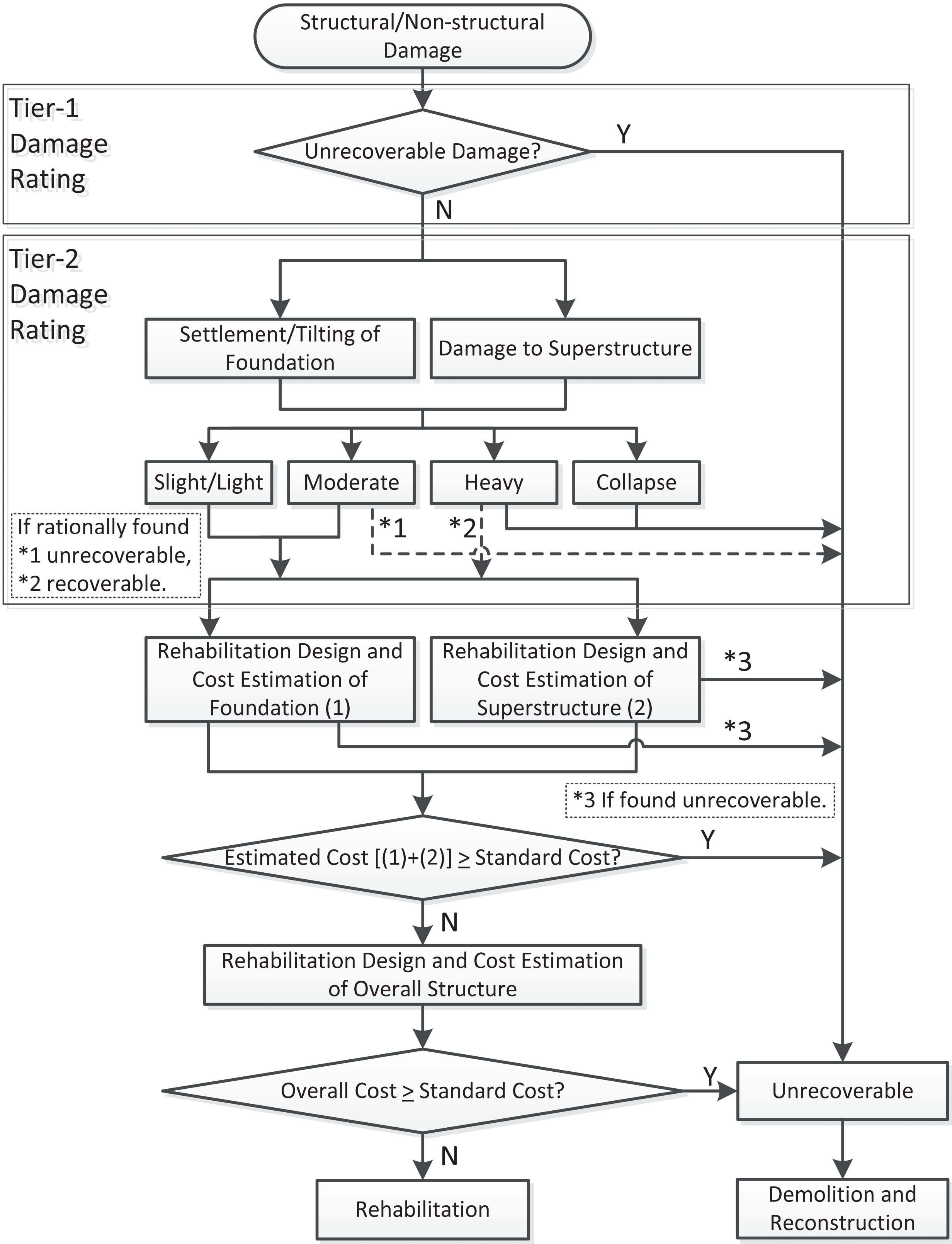

Fig. 2: Two-tiered damage rating procedure for RC school buildings [after 7]

Note that the Seismic Evaluation Standard [10] has been widely applied to existing RC buildings in Japan to implement the nationwide seismic evaluation and rehabilitation program after the 1995 Kobe earthquake, where *Is*-index which denotes the structural capacity index defined by the product of strength index *C* and ductility index *F*, and the relevant structural calculation documents as well as each index value were generally provided. Considering such better-prepared situation, *R*-index defined by the ratio of the post-earthquake *Is*-index to the original *Is*-index was employed in the revised 2001 Guidelines [8].

5. Findings from Damage Assessment Activities

Data collected and investigated through damage assessment activities can be summarized as follows.

5.1 Damage statistics

In the last five decades, the seismic design code was revised in 1971 and 1981 in Japan. **Fig. 3** shows the damage statistics of RC school buildings due to the Kobe earthquake [11]. As can be found in the figure, the damage rate of buildings highly depends on the code generation, and those designed under the pre-1981 code had a higher possibility of more serious damage. This damage trends were widely found in other building use in the Hanshin-Awaji district, and various integrated efforts have been directed by the GOJ and engineering professionals toward upgrading seismic performance of vulnerable buildings and implementing learned and re-learned lessons for earthquake loss mitigation. Several new laws were promulgated soon after the even such as *Special Measures Law on Earthquake Disaster Prevention* and *Law to Promote Seismic Rehabilitation*. Along with these actions and recognizing the serious vulnerability of older buildings, especially of those designed under out-dated code, the MEXT launched a nationwide five-year project for seismic evaluation and rehabilitation of school buildings in 1996. It was extended several times until 2015, through enhancing a subside program to financially support the local government and publishing technical guides to help engineers determine technically and economically sound solutions of rehabilitation to upgrade their performance. **Fig. 4** shows the increasing trends of school buildings seismically upgraded in Japan. Due to these efforts to date, almost 100% of school buildings are provided with required structural capacity [12].

5.2 Damage assessment and damage rate criteria

The damage assessment procedure and its criteria to define damage rate that is employed in the Tier-2 damage rating were calibrated through observed damage. **Fig 5** shows the comparison between the residual

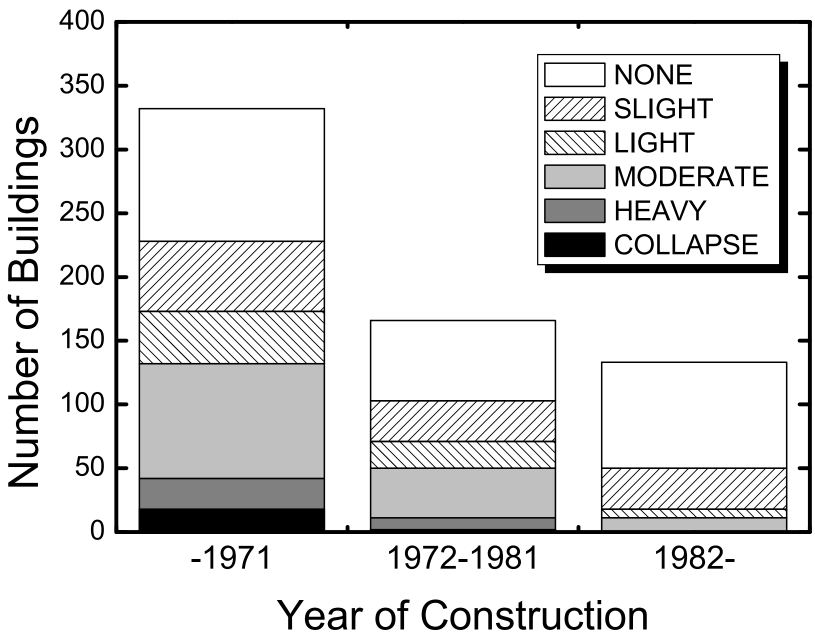

Fig. 3: Damage statistics of RC school buildings due to the 1995 Kobe earthquake [11]

seismic capacity ratio index *R* [8] and judgement by experts of 145 RC school buildings that experienced the 1995 Kobe earthquake [9]. Based on the results shown in the figure, the Guidelines defines the damage rating criteria shown below.

[Slight] $95\ (\%) \le R$
[Light] $80\ (\%) \le R < 95\ (\%)$
[Moderate] $60\ (\%) \le R < 80\ (\%)$
[Heavy] $R < 60\ (\%)$
[Collapse] Building which is deemed to have $R \approx 0$ due to overall/partial collapse

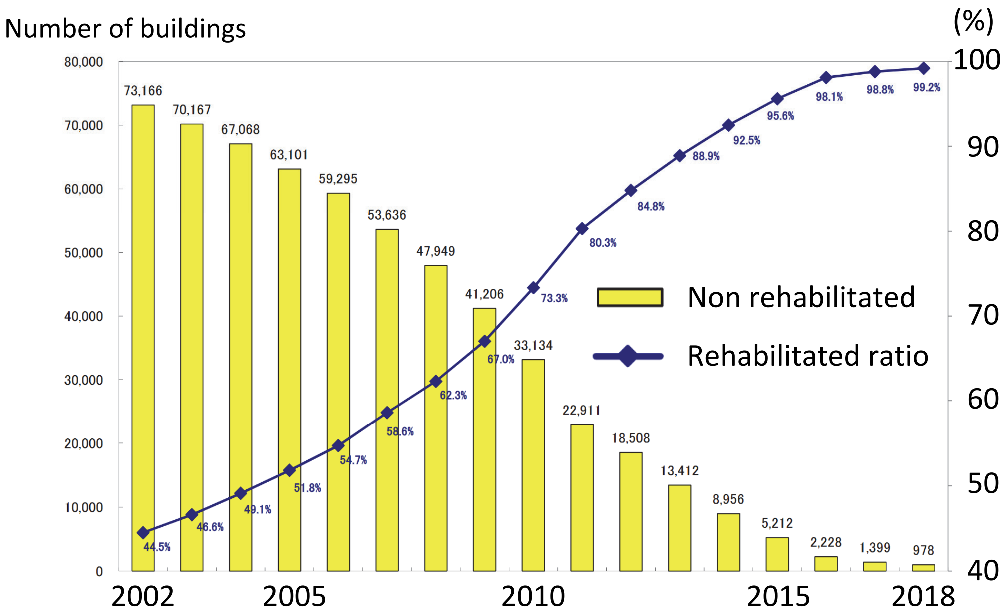

Fig. 4: Ratio of schools with required seismic capacity [12]

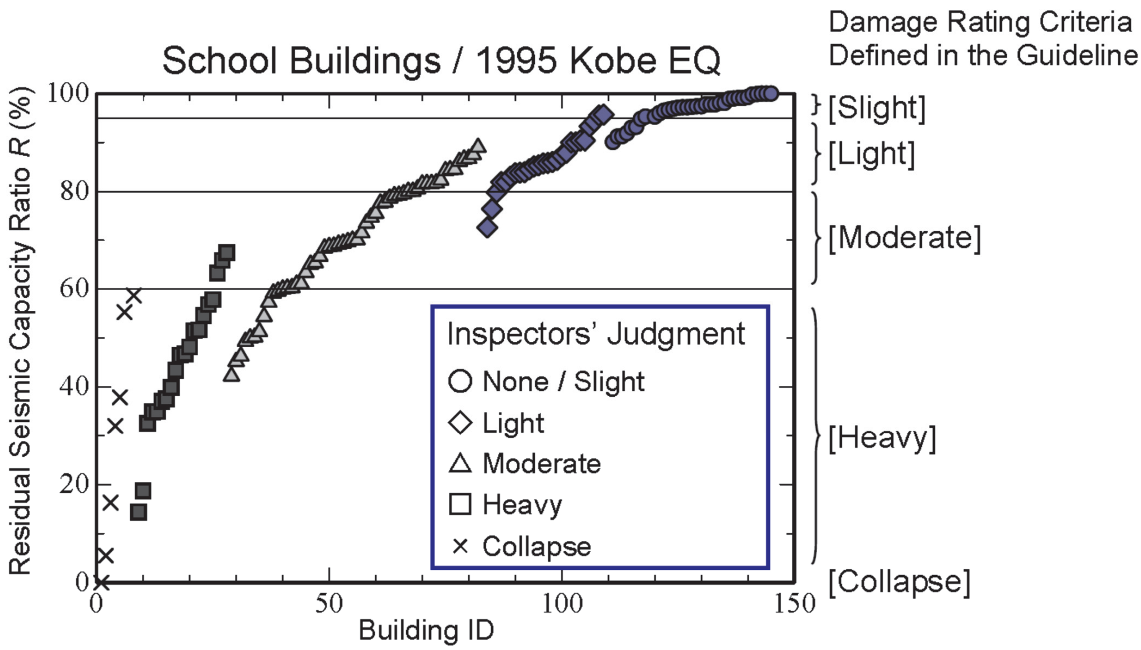

Fig. 5: Residual seismic capacity ratio *R* vs. observed damage [9]

It should be noted, however, that the boundary between two adjacent damage rating such as [heavy damage] and [moderate damage] is not necessarily explicit and some overlapping or gray zones may be found in the figure. Those close to the damage rating criteria should be categorized after careful damage examination rather than a simple numerical judgement.

Maeda made a follow-up study to investigate actions taken by the local government (i.e., building owner of public schools) after 1995 Kobe earthquake [13]. **Figs. 6** and **7** show the relationship between damage rating of RC school buildings and actions taken after the event, either "recovery" or "reconstruction after demolition." As can be found in the figures, most of collapsed or severely damaged buildings were reconstructed after demolition, while those with or less than light damage and two-thirds of moderately damaged were recovered after repair and/or rehabilitation. Maeda also investigated the relation between the actions and the *R*-index described earlier, and pointed out that roughly 60% in *R*-index corresponded to the boundary between recovery and reconstruction, and *R*-index could serve as an index to define the limit state of recovery of RC buildings in Japan although the cost was undoubtedly a key factor for recovery decision.

5.3 Seismic evaluation and required capacity criteria

The Seismic Evaluation Standard was first systematically applied to damaged school buildings after 1995 Kobe earthquake and the relation between seismic capacity index *Is* and damage level was statistically

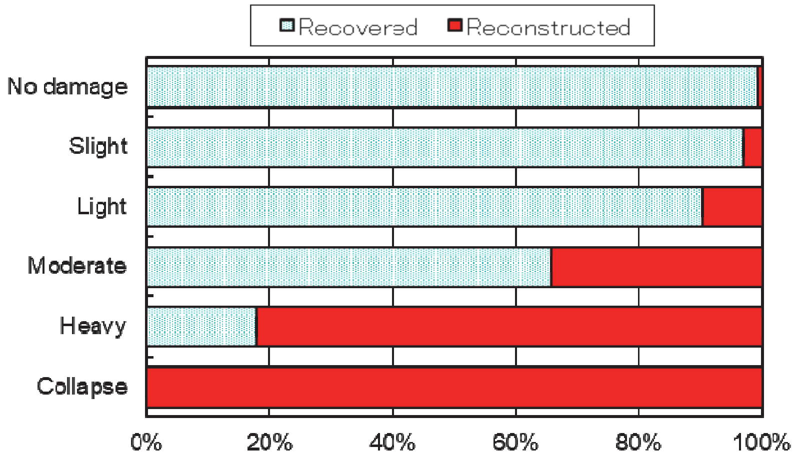

Fig. 6: Recovery ratio of damaged RC school buildings after 1995 Kobe earthquake (after [13])

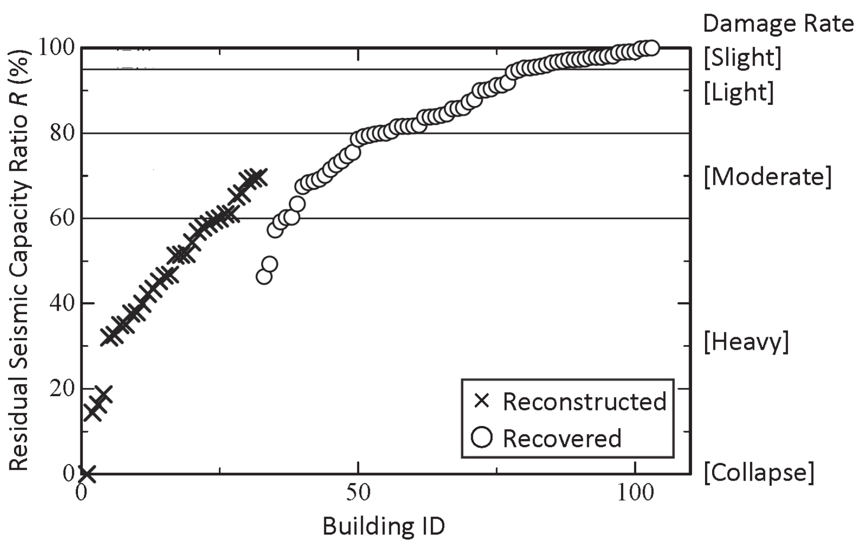

Fig. 7: Recovery criteria and damage rate (after [13])

examined. The results demonstrated that the *Is*-index was clearly correlated with observed damage level; buildings with lower seismic capacity index poorly performed and some had seriously damaged or even collapsed but those with index higher than 0.6 performed well [14], and seismic evaluation and rehabilitation of vulnerable school buildings were identified most urgently needed.

Considering their important function of school facilities as temporary shelter after disaster, as well as safer educational facility, a higher demand of 0.7 in *Is*-index was recommended for school buildings while its standard value was 0.6.

5.4 Cause of damage to be considered in the seismic design and redesign

As has been repeatedly found in the past damaging earthquakes, columns poorly confined with lateral reinforcement suffers more serious damage. In recent years, the ratio of public school buildings with required seismic capacity including those seismically rehabilitated is more than 99% in Japan as shown in **Fig. 4**, and locally 100% such as in Kumamoto city at the time of the 2016 event. Upgraded structural capacity generally leads to no or limited damage to structures. Some buildings, however, often sustain damage due to large deformation that need repair as shown in **Photo 4**. This is because the primary objective of the seismic design and redesign focuses on collapse prevention to eliminate loss of human life. Structural damage control design/redesign, i.e., strength oriented rather than exceedingly ductility oriented design, is most needed to buildings such as schools that are expected to be functional as evacuation shelters immediately after an event.

Damage to non-structural members, such as ceiling, interior wall, etc. has been highlighted in recent events since the structural damage to school buildings has been much reduced due to upgraded structural capacity. Due to such changing trends of observed damage, the MEXT revised the Guidebook [15] for seismic upgrading of non-structural members. It should also be noted that such damage to non-structural members is often found in relatively flexible buildings, causing a large response during an earthquake. Upgrading of seismic performance of non-structural members, considering together with structural response (or drift) controls, is therefore addressed in the damage reports [5 - 7].

5.5 Tsunami issues

Tsunamis after the 2011 Great East Japan earthquake caused remarkable damage to houses and buildings including schools, but the damage rating procedure for tsunami damage was not defined in the 2001 Guidelines, since it was primarily designed to rate damage to structural members caused by ground shakings, not to non-structural members. Devastating damage to RC structures caused by huge tsunamis followed by enormous debris surge was primarily found in non-structural members while the structure itself generally had very minor or even no damage. Such buildings were generally classified into [Slight] or [No] damage although tremendous recovery efforts and time were needed. To facilitate inspectors and building owners to judge the damage in a more rational way, the Guidelines was then revised in 2016 to newly employ the definition of damage by tsunami considering inundation depth in addition to damage by ground shakings.

a) Relocated to elevated ground

b) Redesigned with elevated structural system

Photo 5: Renewed schools after tsunami disaster in 2011

Reconstruction and its location of tsunami damaged buildings was also an essential issue to ensure the safety of buildings to the future potential disaster risk. **Photo 5** shows some examples of reconstructed buildings. Some buildings were relocated inland and/or in an elevated ground, and others were reconstructed with a structural system elevated above the expected tsunami inundation depth.

6. Concluding Remarks

Damage to school buildings due to recent major four damaging earthquakes in Japan was reviewed, and damage assessment activities, which were directed by AIJ special committee members to help local governments and engineers judge necessary actions to be taken for damaged school buildings, were presented. Lessons learned and re-learned through these activities and efforts that should be implemented to further mitigate damage and to develop resilient society were also discussed.

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