Chapter 2
Damage Assessment in Japan and Potential Use of New Technologies in Damage Assessment

K. Kusunoki

Abstract Right after an earthquake, it is quite important to evaluate the damage level of the buildings in the affected area. In Japan, a rapid inspection is conducted to evaluate the risk of collapse due to an aftershock. If any damage is detected, it is required to conduct damage classification, which takes time but categorizes its damage into five damage categories. Japan has a standard for both rapid inspection and damage classification. They are briefed in this chapter. Similar to the damage classification, the loss of the house and home contents for the earthquake insurance. The method for earthquake insurance is also introduced. Since they are based on visual inspection, it is quite difficult to investigate the damage of the high-rise buildings and buildings covered by finishing. Recently, many kinds of research are conducted to use sensors for automatic and realtime damage classification. A structural health monitoring method with accelerometers based on the capacity spectrum method, which is currently installed into more than 40 buildings, is also introduced.

2.1 Introduction

Japan is one of the earthquake-prone countries. We apply a seismic code that requires a very high seismic performance of which base-shear coefficient demand for the short-period building is 1.0. Since the demand is too high to keep the buildings elastic, non-linear behavior such as flexural yielding is accepted to dissipate the input energy safely and to reduce the demand. The base-shear coefficient demand for the most ductile reinforced concrete building is 0.30. It can be said that the buildings may suffer damage during a severe earthquake.

Rapid inspection of existing structures soon after a big earthquake is crucial in order to prevent tragedies due to aftershocks. Civil infrastructures such as public buildings that are supposed to be used as shelters need to be evaluated to find out the seismic performance during aftershocks. On the other hand, it is also very important

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to screen out the buildings that still have enough seismic capacity soon after a mainshock, since a lot of people may refuge from their houses due to fear of collapse even if they have enough capacity. It can help reduce the number of refugees.

In this chapter, the rapid inspection method in Japan (Japan building disaster prevention association 2015) is introduced. If any damage is detected, the damage level is classified into six classes, “none”, “minor”, “slight”, “moderate”, “severe”, and “collapse” according to the more detailed investigation. It is called the damage classification method. The standard is available in Japan to classify the damage of the affected building and to evaluate the capacity if strengthening is needed when it is repaired. The outline of the standard is also introduced.

Same as the rapid inspection, the damage level of the affected building needs to be evaluated right after an earthquake for earthquake insurance. The amount of insurance payment should be paid according to its damage level. The method of the rapid damage assessment for earthquake insurance is also introduced in the paper (The general insurance association of Japan 2019).

Currently, buildings have to be inspected one by one by engineers or researchers according to the above three methods. For example, 5,068 engineers and 19 days were needed to conduct the rapid inspection with 46,000 buildings on a damaged area at the Kobe earthquake. Nineteen days were too long, and yet the number of inspected buildings was not enough. Moreover, many buildings were judged as “Limited entry”, which needs a detailed assessment by engineers. “Limited entry” judgment is a gray zone, and it could not take away anxieties from inhabitants. Furthermore, the current rapid inspection system presents a dilemma since buildings should be inspected by visual observation of engineers. Thus, judgment varies according to engineers’ experience.

In order to solve the problems mentioned above, the author has been developing the real-time residual seismic capacity evaluation system, which needs only few relatively inexpensive accelerometers. The system calculates the performance and demand curves from a measured acceleration of the basement and of each point of a structure with inexpensive accelerometers, and further estimate the residual seismic capacity of a structure by comparing these curves. To draw the performance curve, the absolute response accelerations, and relative response displacement at each point are needed. The displacements are derived from the accelerations by the double integral in the system. The outline of the system and the result obtained from the recorded data of an instrumented building during the 2011 Tohoku Earthquake will be presented.

2.2 Rapid Inspection Method in Japan

The rapid inspection method and the damage classification method were developed by the project “Development of the restoration techniques for damaged building due to an earthquake” (1981–1985) funded by the ministry of construction. Manual for post-earthquake rehabilitation techniques for buildings (draft) was published in

Fig. 2.1 Tags according to the rapid inspection result (Japan building disaster prevention association 2015)

1986. The manual says that the rapid inspection is for evaluating the risk of collapse and falling of nonstructural elements, and for tagging “Unsafe”, “Limited Entry”, and “Inspected” as shown in Fig. 2.1 (Japan building disaster prevention association 2015).

The rapid inspection method is applied in Japan to “rapidly” figure out risky buildings against consequent aftershocks. The inspection is based on the visual observation from outside of the buildings. The risks of both structure and foundation are assessed accordingly. The damage levels of the structural members are classified into five damage classes according to their crack patterns and their residual crack width. Firstly, each member is categorized as “flexural member” and “shear member” by the damage pattern or construction year. Secondly, the damage of the member is classified according to the residual crack width, category, and damage condition, as shown in Table 2.1. Each damage class is conceptually defined based on the dissipated strain energy E_d and remaining strain energy E_r, as shown in Fig. 2.2.

The damage of the structure is evaluated with Table 2.2. The inspection is conducted for the most damaged story. If the damage of any member is classified as Damage Class III, IV, or V, the building is classified as “Rank B”. If the ratio of the number of the columns classified as Damage Class IV and V is high, the building is ranked as B, or C. If the inclination due to uneven settlement is large, it is ranked as B or C. The risk of neighboring buildings and foundation is also taken into account. With all evaluated ranks, the building is categorized as “Unsafe” if there is a Rank C or more. If all risks are evaluated as Rank A, the building is categorized as “Inspected”. Other buildings are categorized as “Limited Entry”.

The inspector must be 1st or 2nd class licensed architect or timber building architect who is living in the affected area. The inspector needs to take a lecture provided by the local government and to be registered. The rapid inspection is supposed to start soon after an earthquake and to finish within seven days.

Table 2.1 Damage class according to the guideline (Japan building disaster prevention association 2015)

Damage class	Condition	
	Flexural member	Shear member
I	Just fine cracks (width < 0.2 mm) exist, but no reinforcement is supposed to yield	
II	Member may yield, and visible cracks exist at its ends (width 0.2 mm ~ 1.0 mm)	Visible shear cracks exist (width 0.2 ~ 1.0 mm)
III	Non-linear deformation increases and relatively wide flexural cracks (width 1.0 mm ~ 2.0 mm) are visible, but cover concrete does not fall much, and core concrete is sound	Multiple shear cracks, of which width is relatively wide, are observed (width 1.0 mm ~ 2.0 mm), but cover concrete does not fall much, core concrete is sound, and restoring force seems to remain
IV	There are many wide cracks, cover concrete falls a lot, and core concrete gets damaged, and reinforcement is visible. Lateral force carrying capacity may be reduced, but columns and walls still carry the gravity load	There are many wide shear cracks, cover concrete falls a lot, and core concrete gets damaged, but buckling/fracture of rebar or hoops are not observed. Lateral force carrying capacity may be maintained
V	Rebar buckled, and even core concrete falls. It seems almost no lateral load carrying capacity is left. Columns/walls shorten. Inclination or settlement may be observed. Rebar may fracture	

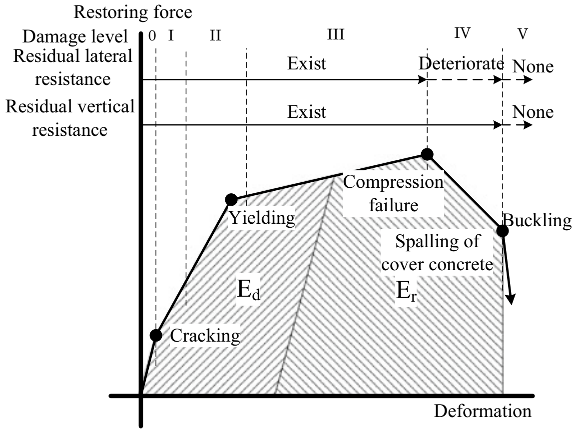


Fig. 2.2 Damage class according to the energy dissipation (Bunno et al. 2006)

Table 2.2 Rapid inspection result according to the risks of foundation and structure (Japan building disaster prevention association 2015)

	Rank A	Rank B	Rank C		
(1)	Damage level III or more exists	No	Yes	–	
	Neighboring building or foundation looks dangerous	No	Unknown	Yes	
	Inclination due to uneven settlement	<1/60	1/60–1/30	1/30<	
		Damage of column (The most severely damaged floor th floor)			
(2)		Num. of columns with damage level V inspected ratio %	<1%	1–10%	10%<
		Num. of columns with damage level IV inspected ratio %	<10%	10–20%	20%<
	Judgment	Inspected All are rank A	Caution Only one rank B	Unsafe Others	
Overall judgment (Take worse case between (1) and (2)	Inspected	Caution		Unsafe	

The risks of the non-structural elements, window and frame, wet and dry finishing, signboard/machinery, outdoor staircase, and other, are evaluated with Table 2.3. If all risks are evaluated as Rank A, the building is categorized as "Inspected". Other buildings are categorized as "Limited Entry". Finally, the building is tagged with the worse category among structural and non-structural damage categories.

2.3 Damage Classification

Once structural damage is observed, a more detailed assessment is needed to evaluate if the building should be repaired or demolished according to not only the damage level but also the seismic intensity at the site. "The standard to classify the damage level due to an earthquake" is applied for the assessment. Firstly, the seismic index of the building without considering the damage, I_s, is calculated with Eq. (2.1).

Table 2.3 Rapid inspection result according to the risks of non-structural elements (Japan building disaster prevention association 2015)

	Rank A	Rank B	Rank C
Window, frame	Almost no damage	Deformed/cracked	High risk to fall
Wet finishing	Almost no damage	Partial damage	Significant damage
Dry finishing	Fine crack in joints	Gap observed	Significant shift
Signboard/machinery	No inclination	Slight inclination	High risk to fall
Outdoor staircase	No inclination	Slight inclination	Significant inclination
Others ()	Safe	Caution	Unsafe
Overall judgment	Inspected All rank A	Caution One or more rank B	Unsafe One or more rank C

$$I_s = E_0 \times S_D \times \mathrm{T} \tag{2.1}$$

where;

E_0 seismic capacity index and calculated with Eq. (2.2).

S_D unbalance index.

T Aging index

$$E_0 = \frac{1}{A_i} \times C \times F \tag{2.2}$$

where;

A_i Restoring force distribution shape factor in the vertical direction.

C Strength index.

F Ductility index.

Secondly, the seismic index with considering the damage, ${}_dI_s$, is calculated. The strength index, C, is reduced according to the seismic capacity reduction factor, η, which is defined according to the damage class, as shown in Table 2.4. The factor is defined based on the ratio of residual strain energy, E_r, to the total strain energy, $E_d + E_r$ in Fig. 2.2.

Table 2.4 Seismic capacity reduction factor, (η Bunno et al. 2006)

Damage class	Flexural member	Shear member
I	0.95	0.95
II	0.75	0.60
III	0.50	0.30
IV	0.10	0
V	0	0

The residual seismic capacity index, R, is defined as the ratio of the reduced seismic index with the reduction factors and the seismic index at the original condition (w/o damage), as shown in Eq. (2.3). According to the value of R, the damage level of the building is classified as "no damage" (R = 1.0), "Slightly damaged" (R > 0.95), "Minor damage" (0.95 > R > 0.80), "Moderate damage" (0.80 > R > 0.60), "Severe damage" (0.60 > R), and "Collapse". The decision of whether to demolish or repair the damaged building is made according to the matrix of both damage level and seismic intensity. For example, even if the damage level is "slight damage", the repairment is not recommended if the seismic intensity at the site is small (less than 5+ according to the standard).

$$R = \frac{{}_{d}I_{s}}{I_s} \tag{2.3}$$

Since it takes at least several weeks and costs a lot to calculate I_s and ${}_{d}I_{s}$, a simplified function is also proposed in the standard. Each vertical member is grouped as a. Flexural member, b. Shear member, c. Plane wall, d. Plane wall with one boundary column, and e. Plane wall with boundary columns at both ends. The strength ratio among the groups is assumed as a:b:c:d = 1:1:2:6. The I_s and ${}_{d}I_{s}$ are calculated with the assumed strength C, seismic capacity reduction factor shown in Table 2.4, and the ductility factor F (=1).

2.4 Loss Estimation for Earthquake Insurance

The earthquake insurance in Japan was developed in 1966 after the 1964 Niigata Earthquake. The insurance aims are to compensate for the loss of houses and home contents to support rebuilding the daily life. The insurance is funded by the government. In this paper, the earthquake insurance for the loss of houses is introduced. When the insurance system was developed, the insurance payment was placed only for the totally collapsed houses. It was changed to have three categories, collapse, half-collapse, and partially collapse, and the amount of payment was decided according to the categories. After the 2011 Tohoku Earthquake, the category was changed to entirely damaged, partially damaged+, partially damaged-, and minor damage. The assigned inspector conducts the estimation.

The category is derived according to the sum of the damage ratio, as shown in Table 2.5. If the sum of the damage ratio is equal to or greater than 50%, 100% of the earthquake insurance premium is paid. The 60, 30, and 5% of the earthquake insurance premium are paid if the damage is categorized as partially damaged+, partially damaged-, and minor damage, respectively.

Firstly, the damage ratio of the whole building is calculated according to the settlement and inclination, as shown in Table 2.6. If the maximum settlement is greater than 100 mm, or if the inclination is greater than 2.1/100, the damage is categorized as "entirely damaged", without calculating damage ratio.

Table 2.5 Earthquake Insurance premium according to the damage (The general insurance association of Japan 2019)

	Damage class	Compensated damage	Insurance premiums paid
Building	Entirely damaged)	The loss percentage of the structure due to an earthquake becomes equal to or greater than 50% of the building	100% of Earthquake insurance premium (up to the actual value of the building)
	Partially damaged+	The loss percentage of the structure due to an earthquake becomes 40–50% of the building	60% of Earthquake insurance premium (up to 60% of the actual value of the building)
	Partially damaged−	The loss percentage of the structure due to an earthquake becomes 20– 40% of the building	30% of Earthquake insurance premium (up to 30% of the actual value of the building)
	Minor damage	The loss percentage of the structure due to an earthquake becomes 3–20% of the building	5% of Earthquake insurance premium (up to 5% of the actual value of the building)

Secondly, the damage ratio of the member damage is calculated. The ratios are listed in Table 2.7, according to the ratio of the number of each damage class to the total number. The ratio is calculated for the most damaged floor. The damage class of members is the same as the damage classification, but the damage classes IV and V are merged into one class of IV. If the number of the damage class IV members exceeds 50%, the building is categorized as “Entirely damaged”, and the damage ratio is not calculated.

2.5 The Structural Health Monitoring System

2.5.1 Outline of the System

The outline of the evaluation is shown in Fig. 2.3 (Kusunoki 2016, 2018; Kusunoki and Teshigawara 2003, 2004; Kusunoki Et Al. 2008, 2012, 2018). The maximum responses during a main shock and aftershock are estimated as the intersection of the capacity and demand curves. The capacity curve is the relationship between the representative restoring force and representative displacement, which are derived from the measured accelerations instrumented into the building, as Fig. 2.4. The demand curve is the relationship between the response acceleration spectrum and response displacement spectrum, which are derived from the acceleration at the basement of the building. The amount of the damping coefficient needs to be assumed when the demand curve is derived. The damping coefficient for the elastic stage can be assumed as the viscous damping ratio of 5% as “Curve 1” shown in Fig. 2.1. When

Table 2.6 Standard table for damage ratios due to settlement and inclination (The general insurance association of Japan 2019)

Damage	Damage ratio (%)	Damage	Damage ratio(%)
Damage of the building	Maximum settlement	① Greater than 5 cm and less than or equal to 10 cm	3
		② Greater than 10 cm and less than or equal to 15 cm	5
		③ Greater than 15 cm and less than or equal to 20 cm	10
		④ Greater than20cm and less than or equal to 25 cm	15
		⑤ Greater than 25 cm and less than or equal to 30 cm	20
		⑥ Greater than 30 cm and less than or equal to 40 cm	25
		⑦ Greater than 40 cm and less than or equal to 50 cm	30
		⑧ Greater than 50 cm and less than or equal to 60 cm	35
		⑨ Greater than 60 cm and less than or equal to 80 cm	40
		⑩Greater than 80 cm and less than or equal to 100 cm	45
		⑪Greater than 100 cm	Entirely damaged
	Inclination	① Greater than 0.2/100 (about 0.1°), and less than or equal to 0.3/100 (about 0.2°)	3
		② Greater than 0.3/100 (about 0.2°), and less than or equal to 0.6/100 (about 0.4°)	5
		③ Greater than 0.6/100(about 0.4°), and less than or equal to 0.9/100(about 0.6°)	10
		④ Greater than 0.9/100(about 0.6°), and less than or equal to 1.2/100(about 0.7°)	15
		⑤ Greater than 1.2/100(about 0.7°), and less than or equal to 1.5/100(about 0.9°)	20

(continued)

Table 2.6 (continued)

Damage	Damage ratio (%)	Damage	Damage ratio(%)
		⑥ Greater than 1.5/100(about 0.9°), and less than or equal to 1.8/100(about 1.1°)	30
		⑦ Greater than 1.8/100(about 1.1°), 2.1/100(about 1.2°)	40
		⑧ Greater than 2.1/100(about 1.2°)	Entirely damaged

the building experience yielding as point (A) in Fig. 2.3, an additional damping effect due to non-linear response needs to be considered. Since the additional damping effect increases corresponding to the damage of the building, the total damping coefficient increases according to the representative displacement. Therefore, the demand curve is reduced from point (B) as "Curve 2" in Fig. 2.3. The maximum response during the main shock is predicted as the intersection of the capacity curve and the reduced demand curve (Curve 2), point (C) in Fig. 2.3.

On the other hand, the same method can be applied to predict the maximum response during an aftershock with considering the main shock and the following aftershock as one very long duration earthquake. The input energy of the combined earthquake is consequently larger than that of the main shock; then the maximum response may be larger than that of the main shock. It means that the equivalent damping effect becomes smaller than that of only the main shock as "Curve 3" shown in Fig. 2.3. The predicted maximum response during the aftershock is the intersection of Curve 3 and the capacity curve, with the assumption that the maximum aftershock is the same as the main shock.

In order to evaluate the safety of the building, the first mode of the response needs to be taken out to derive the capacity curve. The ultimate point is defined with the safety limit of each story. The maximum story drift of each story is derived from the maximum representative displacement and the first mode shape. Since the proposed safety evaluation is based on the first mode, the higher mode effect needs to be considered separately, if the higher mode effect is negligible, such as high-rise buildings (Fig. 2.5).

2.5.2 *Capacity Curve from the Measured Acceleration*

The representative acceleration ${}_s\ddot{\Delta} + \ddot{x}_0$ and representative displacement ${}_s\Delta$ can be derived using Eqs. (2.3) and (2.4) based on the first mode, respectively (Kusunoki et al. 2012):

Table 2.7 Standard table for damage ratios due to member damage (The general insurance association of Japan 2019)

Damage	Damage condition (Physical damage ratio)	Damage ratio (%)	
I	Fine cracks that can be seen in close distance	① Less than or equal to 10%	0.5
		② Greater than 10% and less than or equal to 20%	1
		③ Greater than 20% and less than or equal to 30%	2
		② Greater than 30% and less than or equal to 40%	3
		② Greater than 40% and less than or equal to 50%	4
		② Greater than 50%	5
II	Cracks are clearly visible	① Less than or equal to 5%	0.5
		② Greater than 5% and less than or equal to 10%	1
		③ Greater than 10% and less than or equal to 15%	2
		④ Greater than 15% and less than or equal to 20%	4
		⑤ Greater than 20% and less than or equal to 25%	5
		⑥ Greater than 25% and less than or equal to 30%	6
		⑦ Greater than 30% and less than or equal to 35%	8
		⑧ Greater than 35% and less than or equal to 40%	9
		⑨ Greater than 40% and less than or equal to 45%	10
		⑩Greater than 45% and less than or equal to 50%	11
		⑪Greater than 50%	13
III	Concrete partially crushes, there are wide cracks, and rebar/steel can be seen	① Greater than 3%	2
		② Greater than 3% and less than or equal to 5%	3
		③ Greater than 5% and less than or equal to 10%	5
		④ Greater than 10% and less than or equal to 15%	8
		⑤ Greater than 15% and less than or equal to 20%	10

(continued)

Table 2.7 (continued)

Damage	Damage condition (Physical damage ratio)	Damage ratio (%)	
		⑥ Greater than 20% and less than or equal to 25%	13
		⑦ Greater than 25% and less than or equal to 30%	15
		⑧ Greater than 30% and less than or equal to 35%	18
		⑨ Greater than 35% and less than or equal to 40%	20
		⑩Greater than 40% and less than or equal to 45%	23
		⑪Greater than 45% and less than or equal to 50%	25
		⑫Greater than 50%	30
IV	There are many wide cracks, cover concrete falls down a lot, and core concrete gets damaged, and reinforcement is visible Rebar buckled, and even core concrete falls down	① Less than or equal to 3%	3
		② Greater than 3% and less than or equal to 5%	5
		③ Greater than 5% and less than or equal to 10%	9
		④ Greater than 10% and less than or equal to 15%	14
		⑤ Greater than 15% and less than or equal to 20%	18
		⑥ Greater than 20% and less than or equal to 25%	23
		⑦ Greater than 25% and less than or equal to 30%	27
		⑧ Greater than 30% and less than or equal to 35%	32
		⑨ Greater than 35% and less than or equal to 40%	36
		⑩Greater than 40% and less than or equal to 45%	41
		⑪Greater than 45% and less than or equal to 50%	45
		⑫Greater than 50%	Entirely damaged

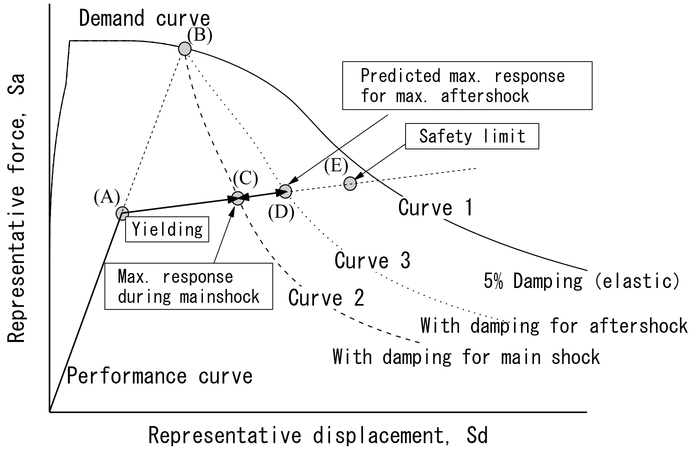
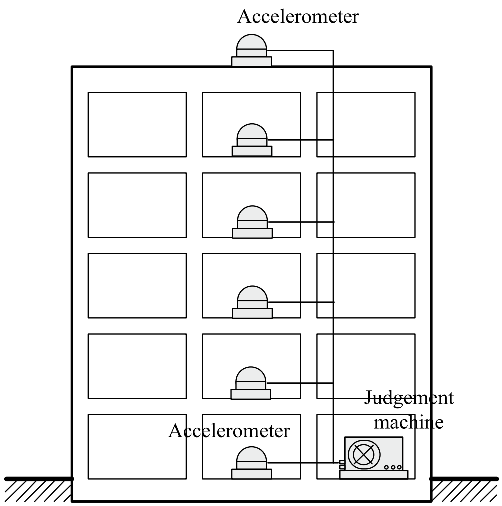


Fig. 2.3 Performance curve and demand curve (Kusunoki et al. 2018)

Fig. 2.4 Configuration of the monitoring



$$\left({}_1\ddot{\Delta} + {}_1\ddot{x}_0\right) = \frac{\sum m_i \cdot {}_1{x_i}^2}{\left(\sum m_i \cdot {}_1x_i\right)^2} \cdot \sum_{i=1}^{N} {}_1P_i \tag{2.3}$$

$${}_1\Delta = \frac{\sum m_i \cdot {}_1{x_i}^2}{\sum m_i \cdot {}_1x_i}. \tag{2.4}$$

The representative displacement can be obtained from Eq. (2.4) by using the relative displacement obtained from the predominant displacement time histories.

The shape of the external force distribution ${}_1P$ of Eq. (2.3) should be proportional to the first mode vector. In order for the absolute acceleration to be proportional to the

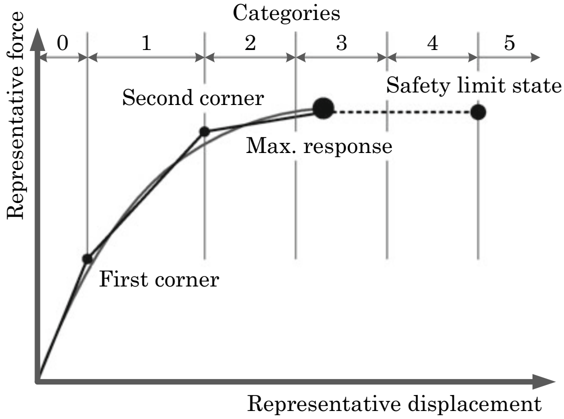


Fig. 2.5 Capacity curve and category of its maximum representative displacement (Kusunoki et al. 2018)

first mode vector, the stimulation factor ${}_1\beta \cdot \{{}_1u\}$ of the first mode must be multiplied by the ground acceleration ${}_1\ddot{x}_0$. This means that the first mode of the unit vector $\{1\}$ is multiplied by the ground acceleration. As a result, the external force proportional to the first mode vector is obtained as.

$$ {}_1P_i = m_i({}_1\ddot{x}_i + {}_1\beta \cdot {}_1u_i \cdot {}_1\ddot{x}_0). \quad (2.5) $$

The representative acceleration in Eq. (2.6) is obtained by substituting Eq. (2.5) into Eq. (2.3):

$$ \left({}_1\ddot{\Delta} + {}_1\ddot{x}_0\right) = \frac{\sum m_i \cdot {}_1{x_i}^2}{\left(\sum m_i \cdot {}_1x_i\right)^2} \sum_{i=1}^{N} m_i \cdot {}_1\ddot{x}_i + {}_1\ddot{x}_{0.} \quad (2.6) $$

As shown in Eq. (2.6), only the relative acceleration term of the representative acceleration is required to be divided by the equivalent mass ratio when the representative acceleration is derived from the measured accelerations.

In Eqs. (2.4) and (2.6), the order of the mass m_i is the same in the denominator and the numerator. Therefore, we require the mass ratio between floors instead of the absolute mass. If the usage of the building is the same for all floors, the floor-area ratio can be used instead of the mass ratio.

2.6 Target Building

The proposed health monitoring system is installed into the building for the department of architecture of Yokohama National University at the beginning of the year of 2008. The building has eight stories and one underground floor. The height of the building is 30.8 m, and its structural type is steel-reinforced concrete. The building was designed before 1981 when the Japanese building code was revised to confirm the ultimate strength of buildings. It was found that the building did not have enough ultimate strength, and then the building was retrofitted. The retrofitting construction had been conducted from July 2008 to May 2009, and the sensors were removed at that time. The building before and after retrofitting is shown in Fig. 2.6. The key plan is shown in Fig. 2.7. EW direction is the longitudinal direction, and NS direction is transverse direction.

(a) Before retrofitting (b) After retrofitting

Fig. 2.6 Instrumented building

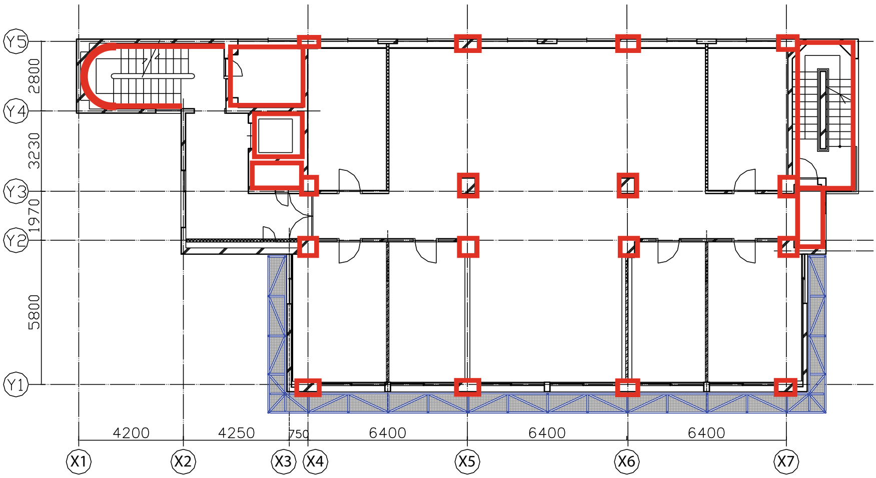


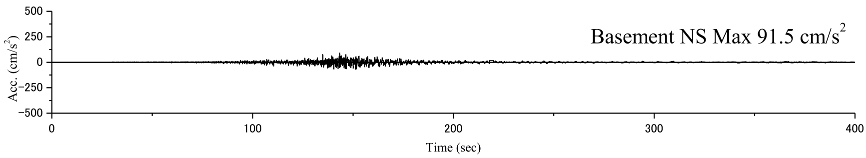
Fig. 2.7 Key plan of the building

After starting the monitoring, 112 earthquakes responses are measured until 2011 Off the Pacific Coast of Tohoku Earthquake, which occurred at 14:36, March 11th, 2011. After that, about 530 earthquake records are measured until the end of 2011.

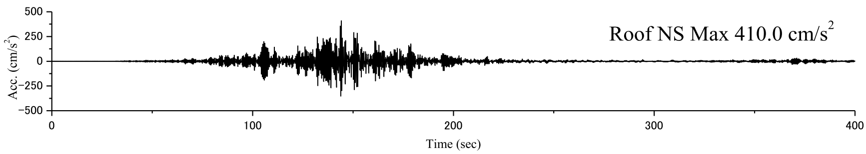
2.7 Response During the 2011 Tohoku Earthquake

The health monitoring system worked well during 2011 Off the Pacific Coast of Tohoku Earthquake (Kusunoki Et Al. 2018). Figure 2.8. shows the measured lateral accelerations on the basement and roof. The maximum acceleration was 91.5 cm/s^2 on the basement and 410 cm/s^2 on the roof. The predominant component of the acceleration lasted about 180 s.

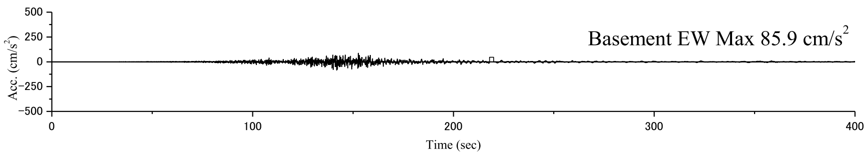
The measured performance curve, skeleton curve from the performance curve, and the demand curve in the EW direction are shown in Fig. 2.9. The vertical axis of the demand curve is the response absolute acceleration spectrum Sa, and the horizontal axis is the response displacement spectrum Sd with the viscous damping



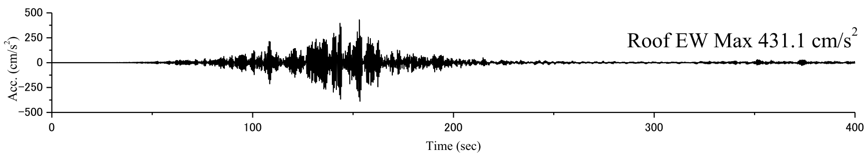
(a) NS direction on the basement



(b) NS direction on the roof



(c) EW direction on the basement



(d) EW direction on the roof

Fig. 2.8 Measured earthquake during 2011 Off the Pacific Coast of Tohoku Earthquake

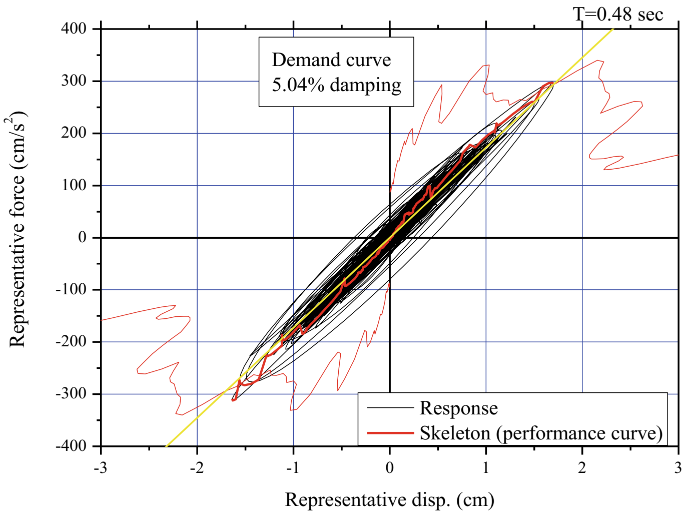


Fig. 2.9 Measured performance and demand curves during 2011 Off the Pacific Coast of Tohoku Earthquake (EW direction)

factor of 5%. The maximum representative displacement of 1.7 cm was measured in the positive direction. The equivalent period from the maximum displacement point in the positive direction was 0.48 s. The calculated viscous damping for the demand curve in order to get the same demand value for the period of 0.48 as the maximum response was 5.04%, which is a reasonable value.

Since the natural period in the EW direction before the earthquake was about 0.41 s, the equivalent period of 0.48 is longer than the period before the earthquake. Figure 2.10 shows the skeleton curve and the slopes for the periods of 0.41 and 0.48 s. It is clearly found that the stiffness degrading started at the representative acceleration of about 100 cm/s^2. The stiffness degraded down to 73% according to the change of the period from 0.41 to 0.48 s.

From Fig. 2.10, it can be said that the frequency change can be observed more accurately from the performance curve than from the transfer function since the slope of the performance curve is square of the predominant angular frequency ω. The transfer function sometimes does not show any predominant frequency if a large nonlinearity occurs during an earthquake. Moreover, while the performance curve shows the building has not yielded yet, it is unclear whether the damage is serious only from the frequency change.

After the main shock, cracks occurred in the building were investigated. The observed cracks in the Y3 frame are shown in Fig. 2.11. Cracks occurred mainly at the bottom of the continuous shear walls and at the corner of openings. These cracks probably cause the stiffness degradation of the performance curve shown in Fig. 2.11.

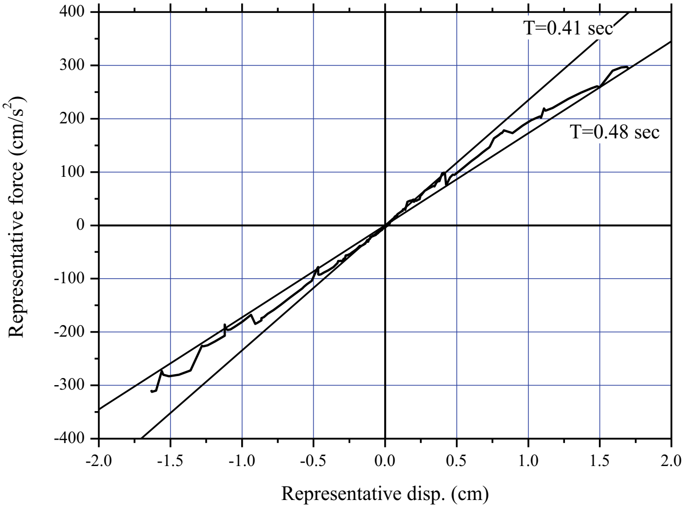
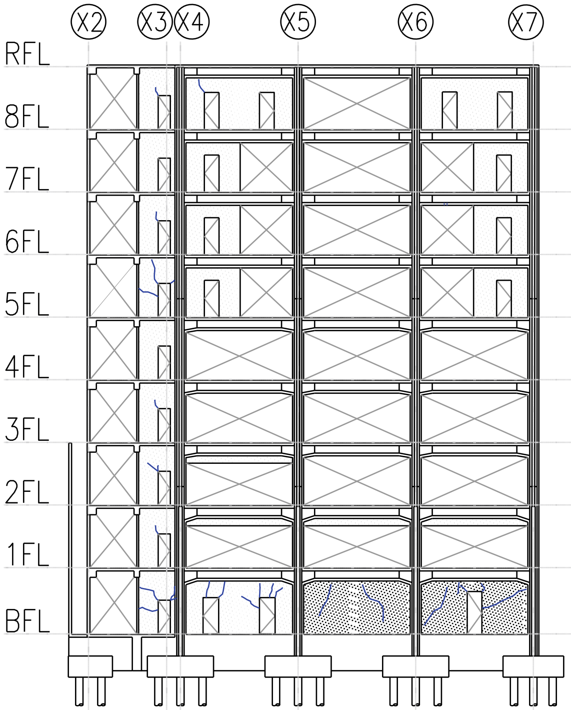


Fig. 2.10 Skeleton curve of the measured performance during 2011 Off the Pacific Coast of Tohoku Earthquake (EW direction)

Fig. 2.11 Observed cracks in the Y3 frame (EW direction)



2.8 Conclusions

The rapid inspection method, the damage classification method, and the loss classification method for earthquake insurance, which are all based on the visual inspection and applied in Japan, are introduced in this chapter. Recent earthquakes revealed that visual inspection is hard to conduct because most of all structural members are covered by finishing, especially for high-rise buildings. Right after an earthquake, it is quite difficult to grasp the outline of the damage, which is needed to decide the target area to inspect. Sensing technology probably helps a lot to overcome the problems. The Ministry of Land, Infrastructure, and Transportation of Japan organized a committee to discuss how to apply the structural health monitoring system for the rapid inspection. The general insurance association of Japan organized a committee as well to discuss how to apply it for shortening the duration to decide the amount of the insurance payment. The sensing technology will be applied widely in the field of disaster reduction soon. Research to bridge the structural health monitoring result and existing inspection method will be needed.

References

Bunno M, Maeda M, Nagata M (2006) Damage classification method for the damaged R/C buildings based on the residual seismic capacity of structural members. Proc Japan Concr Inst 22(3):1447–1452 (in Japanese)

Japan building disaster prevention association (2015) Guideline for post-earthquake damage evaluation and rehabilitation of RC buildings in Japan Part II RC and SRC buildings (in Japanese)

Kusunoki K (2016) Damage evaluation of a base-ısolated building with measured accelerations during Tohoku Earthquake. In: The 16th world conference on earthquake engineering, digital

Kusunoki K (2018) A new structural health monitoring system for real-time evaluation of building damage. Seism Haz Risk Assess 331–343. https://doi.org/10.1007/978-3-319-74724-8_22

Kusunoki K, Teshigawara M (2003) A new acceleration ıntegration method to develop a real-time residual seismic capacity evaluation system. J Struct Constr Eng 569:119–126 (in Japanese)

Kusunoki K, Teshigawara M (2004) Development of real-time residual seismic capacity evaluation system—ıntegral method and shaking table test with plain steel frame. In: The 13th world conference on earthquake engineering, CD-Rom

Kusunoki K, Elgamal A, Teshigawara M, Conte JP (2008) Evaluation of structural condition using Wavelet transforms. In: The 14th world conference on earthquake engineering, CD-Rom

Kusunoki K, Tasai A, Teshigawara M (2012) Development of building monitoring system to evaluate residual seismic capacity after an earthquake. In: The 15th world conference on earthquake engineering, digital

Kusunoki K, Hinata D, Hattori Y, Tasai A (2018) A new method for evaluating the real-time residual seismic capacity of existing structures using accelerometers: structures with multiple degrees of freedom. Japan Architect Rev, Architectural Institute of Japan

The general insurance association of Japan (2019) Contract bookmark for earthquake insurance (revised in January 2019) (in Japanese)