“q-NAVI”: A case of market-based implementation of structural health monitoring in Japan

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Abstract

In Japan, structural health monitoring (SHM) of building structures began in the 1950s, but, until recently, its widespread use was not realized. A new trend arrived a few years ago, and currently over 850 buildings have SHM systems installed. The most recent SHM systems have been installed voluntarily by owners in the private sector; that is, the major development of recent Japanese SHM has been based on market forces. This article reports on why SHM was not accepted widely in the past, what were the keys for change of the atmosphere, how the building owners evaluate SHM after it is deployed, and what tangible benefits the building owners realize by experience on SHM implementation. To investigate those, an SHM system named q-NAVI is introduced as an example. The system has been deployed for 450 buildings, and they experienced a few significant shakings from recent earthquakes. SHM is also found effective for acquiring information on the quantification of fragility curves for various nonstructural components, using the data samples collected in recent earthquakes.

Keywords

Structural health monitoring, market-based approach, earthquake reconnaissance, actual performance of buildings, nonstructural damage, fragility curves, maintenance of monitoring

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Introduction

Building monitoring began in Japan in the 1950s using a type of strong motion accelerographs called SMAC, developed after the 1948 Fukui earthquake. The Japan Building Research Institute (BRI) installed SMAC in about ten buildings in various parts of the country (Takahasi, 1956). Notably, SMAC captured a first record of buildings that collapsed due to soil liquefaction at an apartment complex in Niigata City during the 1964 Niigata earthquake (Japan National Committee on Earthquake Engineering 1965; Kanno et al., 2000). In the early days of the design and construction of Japanese high-rise buildings (1980s), some seismic monitoring systems were also installed, primarily for the purpose of design verification.

In Japan, SHM deployment began as a response to the problem of deterioration of civil engineering structures, when the national and local governments that manage the civil began to install SHM systems (Fujino and Abe, 2003; Wu, 2003; Yanev, 2003). However, for building structures, the utility of SHM was not understood by owners, and the problem of initial and maintenance costs hindered the installation of SHM for buildings for a long time.

This attitude changed after the 1995 Kobe earthquake and succeeding earthquakes that hit various parts of Japan. These earthquakes highlighted the need for seismic observation to identify the level and location of actual damage and eventually to calibrate the effectiveness of seismic design codes and regulations. As a result, installation of SHM in buildings gradually increased. As a large-scale example, BRI installed accelerographs in nearly 80 public facilities throughout the country (Kashima et al., 2012). Since that time, many records have been collected during large earthquakes, including the 2011 Tohoku earthquake, and analyses of the obtained records have been used to advance our understanding of both input ground motions and building response (e.g. see Kawashima et al., 2012).

In the 2011 Tohoku earthquake, 5.15 million people (as estimated by the Cabinet Office of Japan) in the Tokyo metropolitan region had trouble returning to their homes after the earthquake, and pedestrians overflowed roads, which created a very serious problem throughout the Tokyo metropolitan region. The Tokyo Metropolitan Government enforced an ordinance in April 2013 (Tokyo Metropolitan Government, 2013) that, for the sake of safety, people should remain in their buildings when possible, rather than leaving them. The ordinance states that, when a large shaking occurs, facility managers should confirm the safety of buildings and neighborhoods. If safety is confirmed, people in the building are instructed to wait in it. If a large city experiences serious shaking, however, many buildings will be damaged at the same time, and there will be a serious shortage of engineers who can check the safety of buildings. According to a survey on the availability of structural engineers at a time of serious shaking (Architectural Institute of Japan (AIJ), 2012), two to three weeks are required to complete the manual damage evaluations for high-rise buildings built in the Tokyo metropolitan region. Furthermore, in steel-framed buildings, it is often very difficult to quickly confirm safety, because the structural system is covered with fireproofing and other nonstructural components. It is also notable that managers stationed in buildings are commonly not very familiar with structural engineering concepts and therefore cannot effectively and reliably ascertain the safety or unsafety of the buildings.

All of these difficulties suggest the potential for using SHM for the prompt assessment of building safety, particularly in large metropolitan areas. Building owners, particularly those who manage many buildings and are keen about business continuity planning
(BCP), have come to understand this advantage. This new trend differs notably from the movement we saw after the 1995 Kobe earthquake, in that the installation of SHM is driven primarily by business and market forces rather than by public expenditure. Before the 2011 Tohoku earthquake, the number of instrumented buildings in Japan was in the range of 150. Since that time, the number increased to about 500 in 2016 (Nakamura, 2016), further to about 850 in 2018 (Sugimura, 2018), and continues to rise steadily. It is notable that over 700 buildings among those instrumented are privately owned. This is an indication that the market-based installation of SHM is more effective in Japan for implementing building monitoring than the research-based and public installations.

In this article, we report on the following: what are the motivations for private building owners to invest for SHM, how they evaluate SHM after its deployment, and what tangible benefits they realize by experience of SHM implementation, using, as an example, the data obtained by a workable SHM system. The system, designated as q-NAVIGATOR (or q-NAVI in short), was developed in 2014, and its installation began in 2015. As of March 2020 (in four years and half after the first installation), a total of 450 buildings, all privately owned, have been equipped with q-NAVI. The number constitutes about 60% the privately owned instrumented buildings in Japan. Based on the experience with this SHM system, the key factors in persuading building owners to pay for installation of the SHM system are found: (1) initial cost, (2) system reliability, (3) regular maintenance, and (4) service at the time of emergency. We present an outline of q-NAVI, data obtained from the past earthquakes and the corresponding diagnosis delivered by the system, interaction with building owners and managers at times of actual earthquakes, and quantification of damage to nonstructural components as a by-product of SHM. Possibilities of expanded services using SHM are also touched upon in the last part of the article.

**Adopted structural health monitoring system**

*Concept of development*

Numerous studies have been made in research and development of SHM, including those related to the development of new types of sensors, those associated with allocation of sensors, and those focusing on algorithms for system identifications. With respect to actual applications of SHM, comprehensive documents are also made available (e.g. Naeim, 2013; Naeim et al., 2006). The concept of the SHM system introduced here has been defined as (a) applicability to existing buildings, (b) affordable initial cost, and (c) participation of building owners.

First, considering the serious need for condition assessments immediately after a large earthquake event, the SHM system targets its deployment to existing buildings rather than to new buildings. This makes sense because existing buildings are commonly less resistant than brand new ones. Large cities throughout Japan are populated by a large number of 5- to 15-story buildings, Therefore, the system targets buildings in this height range, rather than very tall ones.

Second, about the initial cost, a preliminary survey to building owners about their willingness to deploy SHM confirmed that many are very interested, but naturally cost is a dominant factor for them. In earlier days, when SHM was installed at the time of new construction (commonly by the constructor), the initial cost of deployment was in a range of 100,000 USD, but such amount of initial investment was found to be significantly beyond what the most building owners can adopt. A serious market survey indicated that an initial
cost of 30,000 to 50,000 USD (depending on the size of the building) was acceptable for many building owners who are keen about BCP.

Third, the regular involvement of building owners in the maintenance of SHM systems is important. This lesson was learned from the bitter experiences in Japan with earlier SHMs. In the past, attempts were made to allocate the initial cost related to the installation of SHM in the construction cost. In such cases, the cost for deploying SHM was paid by the constructor, and their primary motivation was to promote good performance of the high-rise buildings that they constructed. Unfortunately, such an arrangement had no mechanism to support maintenance, and eventually many systems were abandoned once equipment failures occurred. Considering those bitter past experiences, the decision was made that the SHM system should require in the contract a mandatory annual maintenance fee to be paid by the building owner. To make the annual fee acceptable for the owners, it is set up at about 2,000 USD, which is commonly not greater than 0.2%–0.5% the annual cost that the owner shall invest for day-to-day mundane maintenance. This maintenance fee, although small, has the very positive benefit of nurturing the sense of participation in SHM among the building owners, making them feel more obligated to participate in the actions that need to be taken immediately after a large shaking.

System configuration

The standard SHM system adopted in q-NAVI is shown in Figure 1, including multiple accelerographs (simply called sensors hereinafter) that measure the vibration of floors in the building (the number and location of the sensors will be shown later), a PC for analysis, a monitor screen that displays the results, and an uninterruptible power supply (UPS) for supplying power at the time of power loss. The PC and sensors are custom-made, as their performance and quality are supposed very critical. The PC is the one adopted commonly for operation of industrial machines instead of those used in the office. PCs used for such an operation are recognized to be more robust. Detail of the custom-made sensors is presented in the next section. Other devices except for the PC and sensors are off-the-shelf and the ones broadly distributed in the market. They have been adopted to cut the cost and secure reliability. The HUB adopted in the system is Power-over-Ethernet compatible, supplying signals and electricity to the sensors via LAN cabling, and therefore a power supply is not needed for each sensor. The sensors are commonly installed on the floor slab in an electric pipe shaft (EPS) that runs throughout the floors. In building structures, the EPS is a very convenient space to install the sensors because it allows handy vertical cabling and positioning of the sensors at the same location along the height. With this handy EPS available, it normally takes one or two days to complete the installation of sensors and LAN cabling.

The level for triggering the recording is set up for the base floor and at 1.5 in JMA (Japan Metrological Agency) Intensity (equivalent to about 20 mm/s² (0.002g) acceleration). The definition of JMA Intensity is found in JMA (1996) and Campbell and Bozorgnia (2011). Once it is triggered, recording begins, the maximum interstory drift ratio and the maximum floor acceleration are computed by the PC, and one of the three diagnoses—“Safe,” “Caution,” or “Danger”—is announced as commonly done in many emergency risk judgments. “Safe” means that one can stay in the building, the building is not damaged, and it can continue to be used. “Caution” means that some damage is plausible, the damage shall be checked, but there is no risk of building collapse and thus no immediate evacuation is needed. “Danger” means that the building occupants should be
evacuated immediately as there is a risk of collapse during aftershocks. Once the SHM system is triggered, a series of displays, that is, detection of shaking, JMS Intensity, and diagnosis, appear in the PC screen. The diagnosis screen highlights important information such as the date of occurrence, the level of shaking at the base floor, statuses of interstory drift ratio and maximum floor acceleration for each story/floor, and most importantly the diagnosis. The building managers can see the screen, quickly understand the building status, and deliver the message of action to the building occupants. The diagnosis appears in the screen commonly within 1 to 2 min after the shaking.

**Types and number of sensors**

Commonly the choice of sensor is made as a balance between the expected accuracy of sensors and the number of sensors to deploy in a building. Because of the requirement for reliability and robustness, wireless sensors have not been adopted. The most important index to judge a building’s status is the maximum interstory drift ratio, but accelerographs can measure only accelerations. Hence, the acceleration records have to be accurate enough so that double integration of the recorded accelerations can ensure a reasonable estimate of the displacement. Estimation of interstory drift ratio requires subtraction between the displacements estimated for adjacent floors; hence synchronization in time is also critical among the sensors. Rather inexpensive MEMS accelerometers have been available in recent years, which can reduce the initial cost significantly, but large long-period noises are often associated with these accelerometers which are detrimental. With that in mind, the SHM system adopts a conservative approach. For the sensor module (i.e., the detector of vibration), a mechanical capacitive accelerograph using a pendulum is chosen. Many elevators in Japan use the module as a motion detector, and its robustness has been verified through about twenty years’ experience of service. The adopted SHM system makes the measurement range of the module enlarged from a common value of $\pm 2g$ to $\pm 3g$ so that the module can capture a very large shaking. The noise level is set at

![Figure 1. Outline of system configuration adopted in q-NAVI.](image)
not greater than 0.0002g, which is significantly smaller than the level tolerated for elevator modules. With this treatment, even a felt earthquake (ranging 0.001–0.002g) can trigger the module. The module has a frequency characteristic of ±3 dB between 0.1 and 40 Hz so that it can cover the natural period band critical for building response. As for the time synchronization, each sensor has its own sampling clock, and the PC for analysis synchronizes the respective clocks. To ensure accuracy, all modules are inspected using a vibration table, and they are tuned so that the amplitude discrepancy is within 3%. A LAN board is also attached to the module so that the SHM system can be connected to LAN.

The number of sensors to deploy is a critical issue when designing the SHM system. Considering the range of cost that can be afforded by building owners, a smaller number is preferred, and it was decided to deploy one tri-axial sensor per floor (measuring two horizontal and one vertical directions) assuming that floor slabs act as rigid diaphragms. Furthermore, the torsional motion was assumed to be very minor. This is justified, at least in Japan, because the Japanese seismic code is very stringent against torsional response and therefore Japanese buildings commonly have minor torsional behavior regardless of the building height. Note also that vertical responses are not accounted for, with an assumption that they will not influence building damage.

The vertical spacing of sensors significantly affects the total number of sensors needed for a building (and eventually the initial cost for the SHM system). A conventional choice is one tri-axial sensor per story, but placing one tri-axial sensor on a few floors is another option. In the latter case, the displacements of those missing floors are estimated by interpolation. Estimation of the interstory drift ratio is made complicated by noises associated with measured accelerations and by execution of double integration. Estimation also involves subtraction between the displacements estimated for adjacent floors. It means that the drift ratio becomes relatively more accurate when the locations of two estimated displacements are farther apart (i.e. with more stories in between).

As a compromise, the SHM system adopts a rule such that the deployment of four tri-axial sensors is the standard case for mid-rise office buildings of around ten stories, which are most frequently constructed in urban areas in Japan and have the largest potential of SHM installation. According to the investigation into modal decomposition (Lopez and Cruz, 1996; Morii et al., 2017), the overall response can reasonably be estimated (with an error tolerance of 5%–10%) if the lowest three modes are taken into account. The first mode natural period of most ten-story Japanese buildings ranges from 0.8 to 1.2 s, and the third mode natural period ranges from 0.2 to 0.3 s. These values suggest that the natural periods corresponding to the fourth and higher modes are unlikely to coincide the predominant periods of ground motion observed in Japan; hence their responses would remain marginal. For these reasons, arrangement of four sensors, by which the lowest three modes can be estimated, has been chosen as the standard.

The number of sensors is adjusted according to the number of floors and the uniformity of structural configuration along the height. As for the interpolation of interstory drift ratios, a simple linear interpolation is used for low- to mid-rise buildings, and a cubic-spline (Naeim et al., 2006) or a mode-based (Goel, 2008; Suzuki et al., 2008) interpolation is adopted for high-rise buildings. Some studies (e.g. Skolnik and Wallace, 2010) address the limitations of such a classical approach to guarantee sufficient accuracy in estimation. We are aware of these limitations; nevertheless, the proposed scheme has been employed considering a delicate balance between cost and accuracy. Furthermore, the current system is believed to be useful for regular buildings (with minimum eccentricities and relatively
uniform strength and stiffness distributions along the height) and for responses only up to mild inelasticity (with the maximum interstory drift ratio not greater than about 2%–3% even for the most ductile structures). Note that the instances of monitoring during actual earthquakes did not reveal any result against the procedures chosen for the SHM.

**Characterization of diagnosis**

The boundaries among “Safe,” “Caution,” and “Danger” are determined in reference to the maximum interstory drift ratios, which vary according to the type of structure. The boundary between “Safe” and “Caution” is commonly set at 0.40%–0.67% (1/250–1/150) for RC and SRC (steel-encased concrete) frame structures, 0.29%–0.50% (1/350–1/200) for RC structures with shear walls, 0.45%–1.0% (1/220–1/100) for steel frame structures, and 0.33%–0.56% (1/300–1/180) for steel structures with braces. The boundary between “Caution” and “Danger” is commonly set at 0.67%–1.7% (1/150–1/60) for RC and SRC frame structures, 0.40%–0.83% (1/250–1/120) for RC structures with shear walls, 1.0%–1.7% (1/100–1/60) for steel frame structures, and 0.67%–1.3% (1/150–1/80) for steel structures with braces. Standard values for respective categories have been determined in reference to the past data and analysis on damaged buildings, which were collected in post-earthquake reconnaissance and risk evaluations (Japan Building Disaster Prevention Association 1998, 2012, 2013, 2018). Furthermore, variation within the same category is considered in reference to the expected ductility capacity (Japan Building Disaster Prevention Association 2015). In the course of setting up the interstory drift ratio limits, design documents of respective buildings are scrutinized, and the drift limits are adjusted for each building. Uncertainty related to the interpolation required to estimate the interstory drift ratios of un-instrumented floors, as well as the conservatism for older, seemingly very brittle buildings, is also allowed for in the setting of the limits. These drift ratio limits are sometimes re-adjusted after significant shaking, as will be presented in a later section.

As supplemental information, status for possible damage to nonstructural components is displayed on the PC screen. The maximum floor acceleration is used for indirect estimation of such damage, in which empirical relationships between the maximum floor acceleration and the degree of damage to representative nonstructural components and building contents are used. The screen highlights a warning sign (and suggests human inspection) for stories having floor accelerations that exceed the threshold values. The fundamental natural period and corresponding damping ratio are also estimated using the recorded data and displayed in the PC screen, although those indices are not referred to in damage evaluation. How to utilize such information for enriching the service of SHM is a subject of further investigation.

**Remote system maintenance and Internet browsing system using cloud monitoring service**

Because of the nature of the service supplied by the SHM system to the building owners and managers, its operation must be reliable during an earthquake. To ensure this, the SHM system enforces remote and continuous maintenance. That is, operation monitoring is performed constantly and automatically from a remote server and through a 3G or LTE mobile phone line via a router. If troubles such as communication errors are found, the related devices are reset. If a device failure is confirmed, the device is promptly replaced by a human.
When an earthquake occurs, recorded data and analyzed results are automatically uploaded on a remote monitoring server using a remote maintenance line. These data are also transferred and stored on a cloud server for backup (Figure 1). Furthermore, a cloud service is designed to be available for the building owners and managers, by which the backup and evaluation data can be viewed collectively via Internet. This has been found to be a very convenient service to building owners and managers, and an example will be noted in a later section.

**Applications and operations of adopted SHM system**

**Applications of SHM system**

Installation of the SHM system is most common among real-estate firms, life insurance firms, and general insurance firms that own many tenant office buildings. These companies have come to recognize that SHM is useful as a service to the tenants and also effective in their asset management. Previously, when a large earthquake occurred, building owners and managers had to ask their employees to manually (e.g. by telephone) collect earthquake information and damage status of their own buildings. With these past experiences in mind, they feel that the initial cost of about 30,000 USD to 50,000 USD is affordable. Damaging earthquakes occur more frequently in recent years in Japan, and it has been pointed out repeatedly that the possibilities of even larger earthquakes, such as those expected to occur beneath the Tokyo metropolitan region and those triggered by ruptures of Nankai Trough, are high. These circumstances also stimulate the spread of installation of SHM throughout Japan.

The adopted SHM system has been installed in 385 buildings as of September 2019, about four years since its service began in 2015. As shown in Figure 2, the instrumented buildings are located in urban areas throughout Japan, centered in large cities such as Tokyo and Osaka. An analysis of business deployment indicates that clients who own multiple buildings tend to increase the number of instrumented buildings after reaffirming the usefulness of the system during earthquakes.
Figure 3 shows the distribution of number of stories for buildings equipped with the SHM system, indicating that mid-rise buildings from 5 to 12 stories are most common. This is mainly because many office buildings are built at around 10 stories in Japan’s urban areas. Tenant offices occupy 79% and company-owned offices 12% in the number of instrumented buildings, which means that over 90% of instrumented buildings are used as offices. It also suggests that many owners consider SHM useful as a tool to demonstrate to their tenants that the building owner is keen about disaster awareness and response. Application to condominiums is very limited, because it is difficult to introduce a system that requires an agreement on initial and annual payment when there are many owners who live in the condominium.

**Observed earthquakes**

Commercial application began in May 2015. As of June 30, 2019, the adopted SHM system recorded 552 events, with a total number of more than 7,000 records. Distribution of the epicentral locations of recorded events is shown in Figure 4. The diameter of the circle that shows the epicenter indicates JMA Magnitude $M_J$, and the observed earthquakes range from $3.0 \leq M_J \leq 8.1$ (moment magnitude scale: $M_W \leq 7.9$). Many relatively large earthquakes occurred in the vicinity of the Tokyo metropolitan region where many buildings are equipped with the SHM system.

Besides earthquake-induced data, data caused by vibrations from nearby construction and strong winds (typhoons) have also been recorded. In such cases, the maximum accelerations were rather small, the status was classified as “Safe,” and no problem occurred at all, because building managers at the shaken buildings could easily distinguish such shaking from that caused by earthquakes.

Among the various records obtained by the SHM system, those of the 2018 Osaka earthquake (June 18, 2018) and the 2018 Hokkaido Eastern Iburi earthquake (September 6, 2018) are introduced in more detail.

**The 2018 Osaka earthquake**

The 2018 Osaka earthquake occurred at 7:58 am on June 18, 2018. Its epicenter was in the northern part of Osaka prefecture. The magnitude of the earthquake was $M_J 6.1$ ($M_W 5.5$),
and the depth of the epicenter was 13 km. The maximum JMA Seismic Intensity ($I_{JMA}$) of 6-lower was observed in urban areas of Osaka prefecture. The human casualties were 6, and 369 people were injured. The damaged houses included 18 collapses, 512 partial collapses, and 55,081 damaged without collapse, according to the criteria stipulated by the Cabinet Office of Japan (2018).

Figure 5a shows a map of JMA Seismic Intensity values measured at the base floor of buildings instrumented with the SHM system. This intensity, $I_{JMA}$, is most commonly used in Japan as a scale of shaking amplitude. Campbell and Bozorgnia (2012) indicate that the approximate relationship of the two intensities is such that the JMA Seismic Intensity of 4 ($3.5 \leq I_{JMA} \leq 4.4$) corresponds approximately to $V$ of $I_{MM}$. JMA Seismic Intensity of 5-lower ($4.5 \leq I_{JMA} \leq 4.9$) to $VI$ of $I_{MM}$, JMA Seismic Intensity 5-upper ($5.0 \leq I_{JMA} \leq 5.4$) to $VII$ of $I_{MM}$, and JMA Seismic Intensity of 6-lower ($5.5 \leq I_{JMA} \leq 5.9$) to $VIII$ of $I_{MM}$. Data were recorded in 127 buildings that were shaken, mainly in Osaka prefecture. The maximum JMA Seismic Intensity observed at the base floor of those buildings was 5-upper.

**The 2018 Hokkaido Eastern Iburi earthquake**

The 2018 Hokkaido Eastern Iburi earthquake occurred at 3:07 am on September 6, 2018, with the epicenter in the mid-eastern part of Hokkaido Iburi district. The magnitude of the earthquake was $M_J \, 6.7$ ($M_W \, 6.6$), and the depth of the epicenter was 37 km, which brought the JMA Seismic Intensity of 7 in Atsuma town. There were 42 casualties and 762 injured. As for the damage to residential houses, 462 collapsed, 1,570 partially collapsed, and 12,600 were damaged without collapse. As for critical facilities, fire occurred at an oil tank in Muroran city and at a thermal power plant in Atsuma town in Hokkaido. The
latter damage triggered a shortage of electricity supply, causing blackouts in 2.95 million households throughout Hokkaido. The blackout continued for about half a day.

Figure 5b shows a map of JMA Seismic Intensity values measured in the earthquake. The SHM system was in operation in 25 buildings in Hokkaido and Tohoku regions, and the maximum JMA Seismic Intensity observed at the base floor of the buildings was 5-

Operating status during damaging earthquakes

Figures 6a and b show two examples of largest acceleration time histories recorded at the base floors of two buildings: A-Building, shaken in the 2018 Osaka earthquake, and B-Building shaken in 2018 Hokkaido Eastern Iburi earthquake. The maximum acceleration at the base floor observed in the 2018 Osaka earthquake (A-Building) was 4.3 m/s² (0.43g), which was larger than the maximum acceleration 1.6 m/s² (0.17g) observed of the 2018 Hokkaido Eastern Iburi earthquake (B-Building). Both buildings sustained no structural damage, and damage to nonstructural components was about the same between the two buildings. In the 2018 Osaka earthquake, the adopted SHM system was kept in normal operation and there were no missing data in those damaging earthquakes. This is attributed in part to the constant monitoring of operational status by remote checking.

The data recorded by the SHM system were sequentially uploaded to the remote server. The time lag from the occurrence of earthquake to the display through the Internet was about 5 to at most 20 min. Three factors contributed to the time delay: first, the post-trigger waiting time to determine the end of earthquake, along with the data processing time within the SHM system; second, the communication time from the mobile phone router installed in the building to the remote data server; and third, the data processing time, in which the remote server sets up the display data to the cloud service. The building
Managers were able to access the Internet shortly after the main shock and see those data via the cloud service. The 2018 Osaka earthquake occurred in the early morning, before most people started moving to their workplaces. Public transportation stopped immediately after the earthquake, so building managers could not go to the buildings that they manage and maintain. Nonetheless, they were able to collect information on building status very quickly via the cloud service and take appropriate actions without delay. This service was appreciated very much by the building owners.

In one building shaken in the 2018 Osaka earthquake, the maximum interstory drift ratio fell into “Caution” (a slightly larger value than the maximum limit for “Safe”). This building is an old stiff frame structure with SRC shear walls, constructed in the 1970s, and regarded as very brittle, and therefore a conservative threshold value (between “Safe” and “Caution”) was assigned (this was also due to the scarcity of data on damage to such buildings). According to a more detailed survey by a construction firm, conducted at a later time, cracks were found in partition walls, but this was judged to be nonstructural damage. Although the judgment given by the SHM system was found not unreasonable, the obtained response and design drawing were carefully reviewed, and the threshold values among the respective categories (“Safe,” “Caution,” and “Danger”) were modified with the building owner’s permission. As shown in this example, the threshold values can be adjusted and refined based on experience.

In the 2018 Hokkaido Eastern Iburi earthquake, all 25 buildings equipped with the SHM system were judged “Safe.” However, most of the Hokkaido region blacked out immediately due to the shutdown of a thermal power plant at Atsuma town. The SHM systems continued to work for about 1 h until the UPS batteries ran out. Although some aftershock records were missing, it was confirmed that the entire shaking during the mainshock was recorded, the resulting judgment was displayed on screen for all the buildings, and the data were uploaded to the cloud server without a problem. Although the monitor vanished after the UPS battery ran out, the cloud service remained functional and experienced no operational problems. Redundant cloud servers had been established in two distant places to make the adopted SHM system robust. It was also confirmed later that the entire SHM system restarted without problems after the power recovery.

Figure 6. Acceleration time histories recorded at base floor of buildings: (a) “A-Building” during the 2018 Osaka earthquake. (b) “B-Building” during the 2018 Hokkaido Eastern Iburi earthquake.
Analysis of damage data from the 2018 Osaka earthquake

Earthquake damage and observation records of buildings

In the 2018 Osaka earthquake, large ground motion records, with maximum ground acceleration of about 8 m/s² (0.8g), were observed in Osaka prefecture. Some buildings installed with q-NAVI also exhibited large floor accelerations up to 4.3 m/s² (0.44g) at the base floor. The estimated interstory drift ratios remained relatively small, in a range of 0.02%–0.33%. This was likely because the predominant period of ground motion was short (about 0.3 s), and the duration time was also short as shown in Figure 6a. Except for one, all buildings were judged “Safe,” but nonstructural damage was reported in many of those buildings. Discussion ensued with the owners of those buildings, and fortunately the owners accepted the need for investigation, considering the importance of detailed investigation into the nonstructural damage in reference to the upgrading of damage evaluations. Eventually a damage survey was conducted on the 26 buildings in Osaka. This experience confirmed that another strong benefit of SHM is its ability to quantify the degree of nonstructural damage and develop appropriate fragility curves for a variety of nonstructural components. Examples of this ability are shown below.

Classification of the 26 buildings is as follows. With respect to the number of stories, 6 buildings were 5 to 8 stories, 15 were 9 to 12 stories, 3 were 13 to 16 stories, and 2 were 17 to 20 stories. With respect to the decade of construction, 5 buildings were built in the in 1970s, 17 in the 1980s, 3 in the 1990s, and 1 in the 2000s. With respect to the type of material, 18 buildings were SRC, 4 were combined RC and SRC, 3 were steel, and 1 RC. Four of the SRC buildings were connected with expansion joints.

Based on the records observed by the SHM system, Figure 7 shows the relationship between the maximum acceleration of the base floor and the maximum floor response (acceleration and interstory drift ratio), including plots for the two horizontal directions. The maximum interstory drift ratio shown in Figure 7a is at most 0.33% and tends to increase as the base acceleration increases. Figure 7b shows the relationship between the maximum acceleration at the base floor and the maximum floor acceleration. The largest acceleration measured in all floors was 8.8 m/s² (0.90g), one significantly larger than the rest in Figure 7b. This particular record was observed in a building equipped with expansion joints and by a sensor placed near the damaged expansion joint. Most likely, such a large acceleration occurred as a result of pulse-like vibration during its serious failure. Figure 8 is an evidence to support the observation. In the building pair connected by expansion joints, one sensor was installed on the floor in each of the building pair. One of the sensors, installed in one of the building pair, was placed very close (by about 2 m) to the damaged expansion joint. The other sensor, installed in the other building, was placed rather distant (by about 25 m) from the joint. Figures 8a and b show the acceleration time histories recorded by the sensors. The record obtained by the sensor close to the damaged joint exhibits a clear spike whose magnitude reaches 8.8 m/s² (0.90g) (Figure 8a), while the record obtained by the other sensor (placed distant from the damaged joint) does not show any of such a spike (Figure 8b). Excluding this particular record, the maximum floor acceleration is in a range of 5.0 m/s² (0.5g). Figure 7b indicates that the floor acceleration is amplified by a factor of one to three from the base to the top. The maximum accelerations of most buildings exceeded 1.0 m/s² (0.10g), which has been confirmed as the approximate magnitude at which damage to nonstructural components began to occur, particularly in ceilings, from the experience of the 2011 Tohoku earthquake (AIJ, 2012).
A survey was conducted for eight major nonstructural component types, shown in Figure 9. The damage examined in the survey was quantified primarily based on interviews with building managers carried out in about two months after the earthquake. Some damage was already repaired, but in such cases, damage was confirmed by photos taken immediately after the earthquake. Figure 9 shows the damage ratio with respect to the number of buildings that sustained relevant damage. Here, the building is classified as damaged unless it did not exhibit any damage throughout the stories to the relevant nonstructural components. Note that 4 out of 26 buildings were equipped with expansion joints.

Major characteristics observed from the survey are summarized as follows: (1) most nonstructural components around the expansion joints were damaged; (2) many buildings suffered damage to interior walls, partition walls, and ceilings; and (3) 4 out of 26 buildings (i.e. 15%) suffered no damage to nonstructural components.

Among the eight nonstructural components, damage to exterior walls, window glasses, interior walls, partition walls, and doors depends primarily on the interstory drift ratio; hence the relationship between the maximum interstory drift ratio and the damage severity is of primary interest. On the other hand, damage to ceilings, furniture, and building

Figure 7. Relationship of response between base floor and floor sustaining maximum response: (a) Maximum interstory drift ratio; (b) Maximum floor acceleration.

Figure 8. Acceleration time histories recorded at building pair having expansion joints. (a) Recorded by sensor placed near damaged expansion joint. (b) Recorded by sensor placed distant from damaged expansion joint.

**Damage investigation of nonstructural components**

A survey was conducted for eight major nonstructural component types, shown in Figure 9. The damage examined in the survey was quantified primarily based on interviews with building managers carried out in about two months after the earthquake. Some damage was already repaired, but in such cases, damage was confirmed by photos taken immediately after the earthquake. Figure 9 shows the damage ratio with respect to the number of buildings that sustained relevant damage. Here, the building is classified as damaged unless it did not exhibit any damage throughout the stories to the relevant nonstructural components. Note that 4 out of 26 buildings were equipped with expansion joints.

Major characteristics observed from the survey are summarized as follows: (1) most nonstructural components around the expansion joints were damaged; (2) many buildings suffered damage to interior walls, partition walls, and ceilings; and (3) 4 out of 26 buildings (i.e. 15%) suffered no damage to nonstructural components.

Among the eight nonstructural components, damage to exterior walls, window glasses, interior walls, partition walls, and doors depends primarily on the interstory drift ratio; hence the relationship between the maximum interstory drift ratio and the damage severity is of primary interest. On the other hand, damage to ceilings, furniture, and building
contents is more sensitive to the acceleration; hence the relationship between the maximum acceleration at the corresponding floor and the damage severity is most relevant. Detailed investigation of interior walls, partition walls, and ceilings, which sustained relatively large damage ratios, is presented below.

**Interior and partition walls**

Many small cracks occurred in interior and partition walls. Cracks were detected most extensively around core spaces running vertically, such as staircases and elevator shafts, and also around openings, such as doors and windows. Most of them were slight in damage, characterized by fine cracks in the walls. Interior and partition walls were composed of many types of materials and installation methods; hence detailed classification of the walls was difficult. Therefore, the relationship between the maximum interstory drift ratio (of the two horizontal directions) and the damage severity of walls was analyzed without detailed classification into respective types of wall. Figure 10a shows the maximum interstory drift ratio and the number of damage cases. The number was counted with respect to the floor, and if damage occurred at least at one nonstructural component in a floor, the floor was classified as “damaged.” In one case, cracks were observed at an interstory drift ratio of 0.05% in a concrete nonstructural wall at the stair room, but most likely this occurred as a result of the concentration of local deformations in the wall. If this case is excluded, notable damage, that is, cracks, was found to occur from a maximum interstory drift ratio of about 0.1%.

**Ceilings**

As for the damage to ceilings, misalignment of ceiling panels and damage to lights and other equipment attached to the ceiling were observed most frequently. A few ceiling
panels fell, where the maximum acceleration at the corresponding floor was 3.8 m/s² (0.39g). This was caused by collisions between the wall and ceiling. Figure 10b shows the maximum acceleration at the corresponding floor and the number of damage cases that match the definition adopted for interior and partition walls. Minor damage such as misalignment was found to occur beyond a maximum acceleration of about 1.5 m/s² (0.15g).

Summary of nonstructural damage

The survey also confirmed that damage to expansion joints began at a maximum interstory drift ratio of as small as about 0.05% and all expansion joints sustained damage at a maximum interstory drift of about 0.1%; damage to exterior walls began at a maximum interstory drift ratio of about 0.2%, a value larger than what was observed in interior and partition walls; sliding of building contents and furniture began at a maximum acceleration of about 3.5 m/s² (0.36g), a value larger than that observed in the ceilings. Doors and window glasses sustained no damage until the maximum interstory drift ratio of about 0.35%. Figure 11 illustrates an example of fragility curve estimated for interior and partition walls using the data shown in Figure 10a. The interstory drift ratio at damage initiation was taken to follow the log-normal distribution. According to this figure, the damage probability exceeds 50% at an interstory drift ratio of 0.13%. Caution is needed when referring to this curve, because the damage was counted with respect to each floor (i.e. judged damaged if at least one nonstructural component was damaged), and the data were limited for the interstory drift ratio of at most 0.40%.

Immediate future perspective based on past experience

Progressive updating of fragilities of nonstructural components

Establishment of fragility curves for important nonstructural components is very critical in the evaluation of damage, repair costs, and business interruption. As indicated in the 2018 Osaka earthquake, damage to nonstructural components commonly starts significantly earlier than that to major structural components; hence quantification of such fragility
curves is very important when buildings are hit by more frequent, mid-level earthquakes. However, reliable fragility curves are rather limited in availability, because experimental data are few and the history of research efforts on nonstructural components is short. Another factor that makes it difficult to develop fragility curves is that the type, material, specifications, and installation method, among other factors, of nonstructural components are not necessarily standardized. Under such difficulties, observation of actual damage provides us with richest information about nonstructural performance, as evidenced above. However, it should be remembered that observation of nonstructural components alone cannot provide fragility curves. They can be established only when the relevant information on structural behavior, that is, the maximum interstory drift ratio and maximum floor acceleration, is made available. This becomes possible only if the building is instrumented, as were the 26 buildings introduced in the previous section.

**Adoption of new technologies such as wireless sensors**

Conventionally, sensors that measure vibrations have been connected to data processing devices by wires. In SHM of buildings, such connecting wires commonly run through an EPS accommodated in almost all buildings. Attempts have been made to remove wires and make the data transfer wireless. So far, q-NAVI has not been configured wirelessly because of the unreliability of wireless communication, such as data blockage by concrete walls and floors, data missing, data interruption, and time desynchronization. However, whether the sensors are wired or wireless is not a serious issue in most buildings, because a handy EPS is commonly available and therefore an additional cost for wiring remains marginal. From the interaction with building owners and managers, it was also found that they do not mind at all whether SHM is wired or wireless as long as necessary data are collected. Therefore, decision on the adoption of wireless sensors depends on a balance between the reliability of data transmission and the cost for wiring. Advancement of sensor technology is naturally very fast, while sensors in SHM have to be replaced regularly over intervals of, say, a few years. In sum, existing sensors can be upgraded to new, wireless ones once we become more confident in the reliability of wireless communication.

**Verification of actual performance with respect to designed performance**

By analyzing the building response observed by SHM, we can evaluate how the performance predicted in the phase of seismic design/analysis is different from the actual performance. Quantifying the difference may also offer a sensible solution in disputes associated with unexpected damage to buildings. The dispute may be about whether the designer is
responsible for the damage by professional misconduct, or the earthquake force to the building was larger than that stipulated in the design code and therefore the designer is exempted from responsibility. Objective data acquired by SHM shall ensure a scientific basis for the final settling of such disputes.

Summary and conclusions

This article presents a history of the application of structural health monitoring (SHM) to building structures in Japan, along with a description of the current situation in the deployment of SHM systems, market-based service using SHM, and accomplishments of this service. The summary and major findings are listed as follows:

1. In the early days of application of SHM to Japanese building structures, the public sector, including universities, deployed SHM and monitored the motions of buildings primarily out of academic interest. After the 2011 Tohoku earthquakes, the number of buildings installed with SHM increased sharply. A notable recent trend is that the vast majority of SHM has been installed voluntarily by owners in the private sector. The owners want to know the status of buildings immediately after significant shaking, to deliver the information to the building tenants, and to utilize the information for BCP for themselves as well as for their tenants. In a word, installation of SHM in Japan has been driven by market forces.

2. As an example of recent market-based SHM, a system named q-NAVI is introduced. As of March 2020, the system has been installed in 450 buildings. The system configuration, types and numbers of sensors, diagnosis procedures for safety evaluation, and remote maintenance and Internet browsing are summarized.

3. Experiences of the adopted SHM system with respect to real shaking are presented. In the 2018 Osaka earthquake, buildings installed with the systems detected a maximum acceleration of 4.3 m/s² (0.44g) at the base floor. All systems functioned properly and delivered the status message (Safe, Caution, and Danger) within a minute or two to the maintenance offices of the buildings. Managers who supervise the maintenance of their buildings had difficulties in visiting and checking their buildings right after the major shaking because most transportation systems were suspended, but they could still check the statuses of their buildings through the cloud service. In the 2018 Hokkaido Easter Iburi earthquake, a blackout due to the shutdown of a thermal power plant occurred immediately after the main shaking. The UPS functioned properly in all systems, and main shocks were captured without missing data, and the building status was delivered with no delay.

4. From the experience of damage survey to 26 buildings installed with the SHM system, it was found that SHM can effectively facilitate the establishment of fragility curves of a variety of nonstructural components. In reconnaissance after large earthquakes, we commonly observe various types and degrees of damage to nonstructural components and building contents, but it is very hard to estimate the degree of external actions (maximum floor accelerations, maximum interstory drift ratios, and others) that caused such damage. SHM is a solution for acquiring information on such external actions.

5. Based on past experience, an immediate future perspective was briefly described, including progressive updating of the fragilities of nonstructural components, adoption of wireless sensors, and verification of actual performance.
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