Opinion Paper

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Three benefits of "Caution (Yellow Tag)" in SHM-driven condition assessment of buildings: Eight years experience with market-based SHM

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Abstract

In Japan, structural health monitoring (SHM) for building structures has received increased attention since the 2011 Tohoku earthquake, particularly regarding business continuity and functional recovery. Most applications are market-driven, and building owners deploy an SHM system at their own expense so that they can promptly assess the condition of their buildings as one of the tags denoted "Green," "Yellow," or "Red." In 2015, the authors' group began installing such an SHM system, and as of December 2023, 553 privately owned buildings have been equipped with this SHM system. This opinion paper presents the authors' experiences to date on monitoring, utility of data, and interaction with building owners. It conveys three opinions that the authors believe to be most interesting, particularly in the context of the benefits of the "Caution (Yellow)" tag. The article briefly introduces SHM, followed by the specific system in question and the data accumulated over the years in Japan. The first opinion is that the damage criteria, that is, the boundaries among the three tags, should not be considered permanent but subject to updates based on experience and newly acquired data. The second opinion is that SHM is one of the best means to characterize the damage (and fragility) of major nonstructural elements, while "Caution (Yellow)" has inherent relevance to the nonstructural damage, particularly for initial damage states. The third opinion is that "Caution (Yellow)" is a good message for building owners and managers with a solid contingency plan that includes readily available building maintenance workers and engineers. On the contrary, it tends to frighten building owners and managers when

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such a contingency plan is absent, discouraging them from installing SHM. Overall, it presents some valuable insights of interest to those wishing to further such SHM systems on a broader scale.

Keywords
Structural health monitoring, building damage assessment, nonstructural damage, fragility curves, maintenance of monitoring

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Introduction

Structural health monitoring (SHM) is a critical technology used to evaluate the seismic performance of buildings worldwide. SHM involves the use of sensors and data analysis techniques to continuously monitor the integrity and performance of structures, particularly during and after seismic events. This technology has a long and rich history, with significant contributions from researchers and engineers (e.g. Celebi, 2000; Kaya et al., 2017; Los Angeles Tall Buildings Structural Design Council (LATBSDC), 2020). When assessing post-earthquake building safety, traditional approaches involve combining estimated ground motions with estimated building capacities to quickly evaluate structural safety against seismic events (e.g. Jaiswal et al., 2010; Wald et al., 2008). While effective at assessing regional damage distributions, these methods fall short in providing detailed responses for individual buildings, which is where SHM systems offer a distinct advantage. SHM allows for monitoring and evaluation of a building's response, providing critical data that can be used to make informed decisions about safety and necessary interventions. Aiming to promote SHM and support emergency management following earthquakes, efforts have been made to characterize the benefits of installing SHM in buildings (e.g. Giordano et al., 2022; Thöns et al., 2022). Their studies highlight the utility of the "value of information" approach in SHM.

Regarding the actual implementation of building SHM, Japan appears to exercise the most comprehensive and organized efforts to ensure real-time safety assessments and information sharing among building owners, managers, and inhabitants (Kanda et al., 2021). This assertion is supported by communications at the time of this writing with international experts in SHM applications for buildings subjected to earthquakes, including Professor R Boroschek (Chair of SSHM Guideline Committee in the Consortium of Organizations for Strong Motion Observation Systems (COSMOS)), Professor F Naeim (Chair of Technical Committee in Los Angeles Tall Buildings Structural Design Council), and Dr. D Wald (Primary developer of ShakeMap and ShakeCast at US Geological Survey). This capability is crucial for ensuring life safety and business continuity during and after seismic events. The importance of SHM has grown in recent years, especially within the framework of seismic risk management. The primary focus of SHM efforts has traditionally been on understanding the seismic performance and capacity of structures through data and information. However, the instantaneous assessment of building safety and the rapid dissemination of this information remain areas where global practices could improve.

This opinion article first presents the Japanese context in further detail, outlining the developments following notable past earthquakes that have led to the current situation. It pays particular attention to an SHM system, named q-NAVIGATOR or q-NAVI in short. The system, referred to simply as the SHM system hereinafter, is first described in detail, followed by an overview of some of the experiences with it to date. Based on these experiences, three fundamental findings, or "opinions" in this context, given their subjective nature, are outlined and further detailed with supplementary information in the subsequent sections.

SHM in Japan

Background

In Japan, SHM began to be applied to buildings in the 1950s (Takahasi, 1956). The 1995 Kobe earthquake caused severe building damage, including collapse (Architectural Institute of Japan (AIJ), 1995), which encouraged both the widespread installation of SHM to collect data on actual building response, and the calibration of current seismic codes. These incentives naturally resulted in most efforts being driven primarily by the research and engineering communities, and the financial support for the SHM deployment being controlled by the public sector. After the 1995 Kobe earthquake, the number of SHM buildings in Japan was approximately 150 (Kashima et al., 2012). Note also that most SHMs in those days adopted strong motion seismographs named SMAC-type (Takahasi, 1956). The motion was recorded on a tape installed together with the sensor, and humans were responsible for gathering, analyzing, and digitizing the data (recorded on tapes).

The 2011 Tohoku earthquake devastated a large part of Japan primarily because of the tsunami that immediately followed (e.g. Earthquake Engineering Research Institute (EERI), 2013). In addition to various types of damage caused by the earthquake, the Tokyo metropolitan area experienced significant disruption in the immediate aftermath despite the level of shaking not being severe (with a Peak Ground Acceleration of at most 0.2–0.3 g). All public transportation was halted throughout the day, and many people were forced to remain in transit stations or their workplaces rather than return to their homes. The earthquake's aftershocks generally caused them to fear for the safety of the buildings they were temporarily sheltering in. Following those experiences, the local government of Tokyo issued an ordinance in 2013 (Tokyo Metropolitan Government, 2013) that, in an event like the 2011 Tohoku earthquake, people should stay in the buildings they work in rather than try to move or go home, so long as the buildings were deemed safe. The concept was laudable, but the fundamental problem of how to judge or define safety remained unresolved.

Independently of the Tokyo metropolitan government's ordinance, many corporations that owned and managed office buildings in the Tokyo metropolitan area also recognized the significant inconvenience caused by not knowing the status of their buildings immediately after a large shaking event, as the inability to take immediate and solid measures seriously impeded business continuity. A new type of SHM began to appear in response to those emerging needs. This time, the motivation was market-driven (rather than managed by the public sector), since the installation of SHM was done at the building owner's expense, and the objective of this SHM was to provide the building owners, managers, and occupants with the status of their buildings within 1–2 min after an earthquake event. Among several such SHM systems installed in Japanese buildings, the SHM system that has been developed and managed by the authors' institution is briefly described in the following subsection.

Development of the SHM system

The SHM system is a SHM solution designed to enhance building safety in Japan, especially in the context of seismic activity. Developed with a market-based approach following the legislative developments in Tokyo in 2013, the SHM system aims to address the needs of building owners and managers by providing timely and accurate assessments of building integrity following seismic events. The system configuration of the SHM includes multiple custom-made accelerographs to measure floor vibrations, a robust industrial-grade PC for data analysis, a monitor to display results, and an uninterruptible power supply to ensure continuous operation during power outages. The system triggers recordings at a base floor acceleration of $\geqslant 0.002$ g, computes key metrics such as the maximum interstory drift ratio and maximum floor acceleration, and provides one of three diagnostic statuses: "Safe," "Caution," or "Danger." Note that the interstory drift is estimated as the relative difference between adjacent floors, which is calculated by integrating the recorded acceleration responses. These diagnostics appear on the PC screen within 1–2 min after an earthquake, enabling building managers to understand the building's status and take appropriate actions quickly.

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 reinforced concrete (RC) and steel-encased reinforced concrete (SRC) 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 [2011], 2013 [2009], 2018 [2017]). More details are presented in Kanda et al. (2021). It is also notable that, as discussed later in Opinion 1, the damage criteria are not permanent but subject to updates. For instance, O'Reilly et al. (2023) analyzed similar data for nonstructural elements and highlighted how these thresholds can be updated when more data becomes available.

The following procedure has been set up to continuously check the damage statuses of the buildings equipped with the SHM system and check the correlation between the detected damage level and the actual damage disclosed in those buildings.

1. All data obtained for each SHM building are stored and archived permanently in the data server maintained by the SHM operation team. It enables the team, consisting of professional structural engineers, to regularly and routinely examine the appropriateness of the obtained data and evaluate the legitimacy of threshold values that distinguish among "Safe," "Caution," and "Danger." Note, however, that the data belong to the building owner, and therefore, disclosing the data to third parties requires consent from the building owner.
2. A direct line of communication has been set up between the building manager and the SHM operation team for each SHM building so that prompt communication is possible in case of emergency.
3. The data processing unit of the SHM system has been automated so that its recordings, particularly the ones detected by the base floor sensor, can be checked against the observed shaking level expressed as the JMA Seismic Intensity (I_{JMA}) (Suzuki et al., 2023) in which the concerned building is located.

4. If the I_{JMA} is not significant, which is judged commonly when it is not greater than 5-minus, and the SHM records also indicate "no significance" in shaking, the building damage is deemed to be at most minimal.
5. If I_{JMA} is not significant, but the SHM system announces an alert of "Yellow" or "Red," the building manager is immediately consulted about the building's actual status. This situation occurred very seldomly; in one case, an alert of "Red" was given to a building in a past earthquake, although the I_{JMA} in the neighboring region was only 5-minus. After an emergency conversation with the building manager, the SHM system was found to have recorded a large acceleration pulse (reaching 2.4 g) because a panel placed near one of the sensors fell and struck the box housing the sensor. By utilizing the direct line of communication between the building manager and the SHM operation team, they were able to quickly exchange information, identify the cause of the alert, and reassure the building occupants and owner of their safety, without disruption to the building's occupancy.
6. When both I_{JMA} and SHM records reveal significant shaking, say I_{JMA} of 6-plus and stronger, the direct line of communication is activated. It allows information to be exchanged on actual damage, including both structural and nonstructural damage, and the prompt evaluation of the appropriateness of the preset damage categories. If re-evaluation for the categories is deemed reasonable, an investigation team is dispatched to the building for a careful damage status check and also conduct numerical simulation, if found effective, to examine whether the category should be modified or not, and finally change the threshold values after the consent of the building owners.

Note that the experiences thus far have been for when the "Yellow" tag has been encountered, and never "Red." A few SHM buildings sustained maximum floor accelerations as large as nearly 1 g (Figure 3b). Still, they were judged "Caution (Yellow)," as their maximum interstory drifts were not as significant as the level corresponding to "Danger (Red)." Once stronger shaking occurs, and many buildings are tagged "Red," it is likely that a severe shortage of workforce will result, and difficulties in effectively implementing the procedure noted above may arise. This remains a challenge in the current implementation of damage detection using building SHM.

In addition, the SHM system facilitates remote maintenance and data accessibility via cloud services, ensuring that building owners and managers can monitor building conditions and access historical data from anywhere. This capability is essential for promptly addressing any issues that arise and for long-term building performance analysis. Further details on the SHM system are to be found in Kanda et al. (2021).

Experiences with the SHM system to date

Since the installation of the SHM system began in 2015, 553 buildings in Japan have been equipped with it as of December 2023. Figure 1 illustrates their geographical distribution of the SHM buildings. The distribution is summarized as follows. In terms of the year of construction, 17% were built before 1980, 61% between 1981 and 2000, and 22% between 2001 and 2023. Regarding the structural system, 17% were made of reinforced concrete (RC), 55% of SRC, and 28% of steel. As for building height, 15% were between 1 and 4 stories (low-rise), 69% between 5 and 12 stories (mid-rise), and 16% were 13 stories or taller (high-rise). The majority of these buildings are neither particularly new nor tall, which is reasonable since such buildings are considered more susceptible to structural damage. It is also noteworthy that over 82% of the SHM-equipped buildings are used as offices.

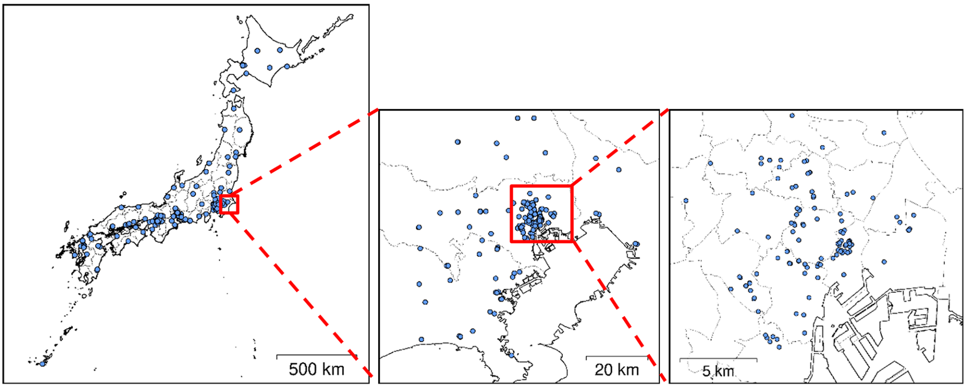


Figure 1. Installation of the SHM system in buildings in Japan (until December 2023).

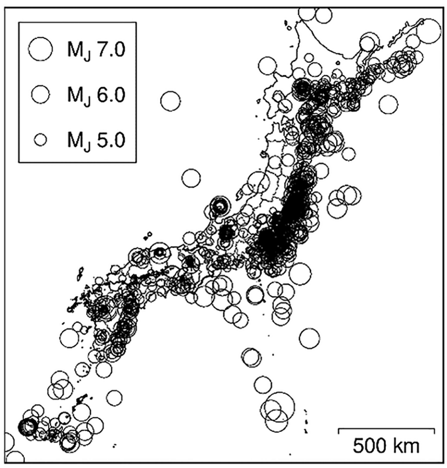
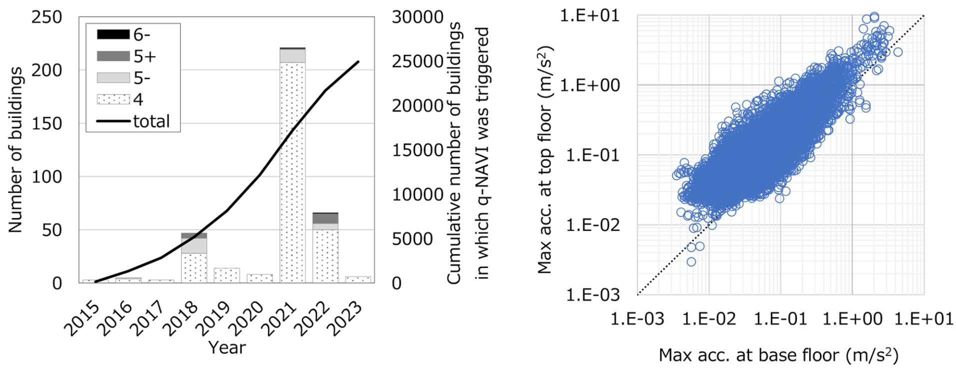


Figure 2. Major earthquakes that occurred in Japan between May 2015 and December 2023.

Figure 2 shows the earthquakes in Japan since 2015 when the SHM system was deployed. The diameter of the circle that shows the epicenter indicates JMA Magnitude M_J, and the observed earthquakes range for $4.0 \leqslant M_J$. The figure includes 1082 data points for $4.0 \leqslant M_J$ and 80 data points for $6.0 \leqslant M_J$, indicating that Japan has been shaken frequently and at relatively large magnitudes. As a means of reference with the moment magnitude, M_W, it can be taken that M_J nearly equals M_W for subduction zone earthquakes not greater than $M_W = 7.0$ (Takemura, 1990).

Figure 3a summarizes how often the buildings installed with the SHM system were shaken by the earthquakes shown in Figure 2. The solid line curve (plotted with reference to the right vertical axis) shows the cumulative number of buildings in which the SHM system was activated and the building response recorded. The plot is made with respect to the year (from May 2015, when the system operation began, to December 2023). Figure 3b plots a total of 24,944 records, most of which are small, not greater than 1 m/s^2, in the maximum acceleration at the base floor (approximately 0.1 g). Still, 115 records (about 0.3% of the



(a) (b)

Figure 3. Earthquake responses of buildings equipped with the SHM system: (a) numbers of buildings in which the SHM system was triggered (until December 2023) and (b) Responses of buildings equipped with the SHM system.

total) go beyond 1 m/s^2 at the base floor, with a few records arriving at as much as 3.3 m/s^2 (0.3 g). The corresponding accelerations at the top floor also reach nearly 1.0 g. The figure indicates that the buildings equipped with the SHM system had experienced not only "small" but also "medium to (relatively) large" earthquakes considered in the contemporary seismic design. Of the 24,944 recorded cases, the system flagged "Caution (Yellow)" seven times from three earthquakes, and hence, the discussions included herein are limited to these key observations. In one such case, the maximum acceleration at the top floor reached 0.97 g (the largest shown in Figure 3b), and the maximum interstory drift was estimated at 1/130, while the threshold value was set at 1/150. The SHM system announced "Danger (Red)" only once in its history, but it occurred because of very local pulse-like loading, as noted in an earlier section.

Lessons learned to date

The authors have thus accumulated many lessons by managing the SHM system. According to a marketing book by Moore (1991), entitled: "Crossing the Chasm: Marketing and Selling High-Tech Products to Mainstream Customers," there are five groups of people and organizations who have different attitudes toward the adoption of new technologies, that is, Innovators, Early Adopters, Early Majorities, Late Majorities, and Laggards. According to Moore, innovative new products shall face the market dynamics characterized as the "chasm" or adoption gap that lies between the early market (Early Adopters) and the mainstream market (Early Majorities). Anyone with an innovation or new product should focus on one group of customers at a time, using each group as a base for marketing to the next group. Transitioning between visionaries (Early Adopters) and pragmatists (Early Majority) is the most difficult step. Following Moore's (1991) propositions, the authors feel that the Japanese SHM appears to have stepped into a stage of having captured "Early Adopters" and struggling for "Early Majorities," that is, facing the chasm noted by Moore (1991).

Based on the lessons accumulated over the past 8 years through the conversation with the building owners and managers who own and manage the SHM, the authors have come to believe that, in the domain of SHM, utilities of "Caution (Yellow)" should be the key to overcome the chasm and promote the SHM. In the following subsection, the authors wish to express their opinions, nurtured via their experiences, regarding (1) damage characterization, (2) nonstructural elements (for those installed in buildings such as interior partition walls, exterior cladding, window glass, and ceilings), and (3) benefits and drawbacks.

Dynamic nature of damage criteria

> ***Opinion 1***: *Damage criteria set up, i.e., "Safe (Green)," "Caution (Yellow)," and "Danger (Red)," are not permanent but subject to updates based on experience and newly-acquired knowledge.*

Immediately after noticeable shaking, the SHM system informs the building manager and inhabitants of one of the three statuses, "Safe (Green, not greater than minimal damage and continued occupancy ensured)," "Caution (Yellow, some damage, no need for immediate evacuation, detailed damage checks recommended soon)," and "Danger (Red, serious damage and evacuation recommended)." The judgment of "Safe" considers a condition in which the stresses induced in major structural members do not exceed their respective short-term allowable stresses. A warning signal for nonstructural damage is triggered when the maximum floor acceleration reaches 0.1 g. As might be expected, determining the threshold values to associate with the three is rather difficult, particularly for old buildings. This is because they tend not to be as ductile as those built with recent design codes, the properties of building materials are more uncertain, the effects of nonstructural elements on the building's strength are difficult to quantify, and experimental data on such old buildings remain scarce. A typical example is an old multi-story RC building (Figure 4), built in the 1970s before the major overhaul of Japanese seismic design in 1981. In such RC buildings, all exteriors are filled with RC walls with openings of various shapes, generally for windows and doors, which form spandrel walls, lintel walls, and wing walls. According to this outdated practice, they were monolithically connected to the surrounding columns and beams, and susceptible to damage from stress and strain concentrations at the joints. The design did not consider such concentrations of strain, and very little effort was spent ensuring ductility in the walls. In cases such as this, where there are many uncertainties, we must be significantly more conservative when setting the threshold values. For RC structures like the one shown in Figure 4, default threshold values for the maximum interstory drift ratio are set at 1/350 and 1/250 for the boundaries among "Safe (Green)," "Caution (Yellow)," and "Danger (Red)." Those values are significantly smaller than the threshold values of 1/200 and 1/120 stipulated for modern RC frames with shear walls. The difference is nothing else but the conservatism attached to uncertainties. However, the conservatism on the threshold values is not fatal since the values can be adjusted, as noted below.

About 85 such old RC buildings have been equipped with the SHM system and were subjected to the earthquakes and ground motions shown in Figures 1 and 3. In two events, the 2018 Osaka earthquake and the 2021 Fukushima earthquake, "Caution (Yellow)" was announced for two such buildings. After the earthquakes, the authors visited these buildings, observed their damage, and confirmed that the maximum interstory drift estimated by the SHM system was reasonable, although the structural damage remained light. This

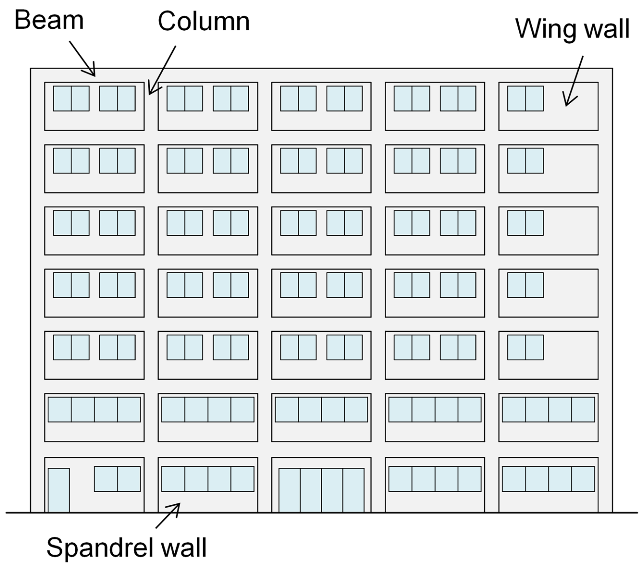


Figure 4. A typical medium-rise RC building constructed in Japan until the end of the 1970s.

was a result of the conservatism, as noted above. With the consent of the building owners, we decided to relax the threshold values for those buildings. This experience was clear evidence that we can learn from actual earthquake responses and adjust the threshold values that separate the damage status to more suitable ones. This is similar to the discussion by O'Reilly et al. (2023) relating to the SHM data collected in these earthquakes. They noted how available fragility functions in the literature are not a bad starting point when no information for a specific building is available, but that accumulated data can be used to update such fragility functions and, consequently, the threshold values, once more data is collected via the SHM system over time. Thus far, the actual data corresponding to significant structural response (eventually labeled "Yellow") remain scarce, as noted above; hence, the threshold values were revised for specific buildings rather than for generic building types. However, by continuously accumulating such data from actual responses and classifying them with respect to the building type, we can establish more reliable threshold values specific to different building types.

Characterization of nonstructural damage

> ***Opinion 2***: *Monitoring is one of the best means to characterize the damage (and fragility curves) of major nonstructural elements, all the while "Caution (Yellow)" has inherent relevance to the nonstructural damage.*

Damage to nonstructural elements and its responsibility for dictating recovery and/or business and life continuity has been a hot subject in Japanese earthquake engineering, particularly after several earthquakes in the middle 2000s (such as the 2004 Chuetsu earthquake (AIJ, 2006) and 2007 Chuetsu-oki earthquake (AIJ, 2010)). The 2004 Chuetsu earthquake caused manufacturing lines to fail at an electronic component plant. It took nearly 5 months for the plant to recover and led to serious business interruption (Cabinet

Office of Japan, 2007; The Small and Medium Enterprise Agency, 2023). In the 2007 Chuetsu-oki earthquake, another plant manufacturing automobile parts severely damaged its machinery. As a result, all 12 Japanese automobile manufacturers had to shut down their production lines because of the interruption caused by the earthquake damage. Having learned from the disruption experienced in the 2004 Chuetsu earthquake, major automobile manufacturers dispatched many employees to the plant. They worked days and nights with the plant's employees and reopened production 2 weeks after the earthquake (Nakano et al., 2008).

The above examples were the damage to manufacturing plants and the disruption of the machinery, which had severely impeded business continuity. Damage to nonstructural elements in office buildings also received more attention since the 2000s when relatively large earthquakes shook many parts of Japan (e.g. AIJ, 2001, 2004a, 2004b, 2005, 2010). Damaged patterns reported following the earthquakes revealed that the initiation and progress of nonstructural damage commonly preceded structural damage, with many instances where damage occurred only in nonstructural elements. It is also worth mentioning that Japan's strong motion networks (K-NET and KiK-net (NIED, 2019)) were in operation by then, and the strong motion data and the severity of nonstructural damage could be correlated more accurately.

Since then, significant efforts have been underway to quantify the nonstructural damage. However, such quantification has been impeded by the following characteristics relevant to nonstructural elements. That is, the performance of nonstructural elements is significantly affected by their connection to the primary structural elements. Good and inadequate detailing meant that the forces applied to the concerned nonstructural elements differed significantly. Furthermore, how to achieve the connection is often proprietary and difficult to classify. Characterizing and classifying such behavior/performance is very difficult in laboratory testing as we must deal with many different types of surrounding structural elements and connections details with the tested nonstructural element. A more detailed discussion on the difficulty in quantifying the nonstructural damage is presented in O'Reilly et al. (2023).

Another difficulty we encounter when trying to quantify the damage of nonstructural elements through laboratory testing is the reproduction of the scale and the boundary to the surrounding elements. Most typical is the ceiling system, which is very crucial among various nonstructural elements, in terms of human safety. However, ceiling failure has been known to depend significantly on the area of the ceiling. If the ceiling is small in area, like the one that can be achieved in the laboratory shaking table test, the likelihood of ceiling failure, such as panel misalignment or falling, is very small. For example, in a shaking table test for a small ceiling system (3.5 m by 1.4 m), there was no single damage up to 1.5 g in the maximum acceleration induced to the ceiling (McCormick et al., 2008). Even with a larger specimen, for instance, a ceiling system of 30.0 m by 18.6 m (Shirasaki et al., 2014), tested using E-Defense (Nakashima et al., 2018), the ceiling system remained nearly intact with the maximum acceleration of 1.5 g. It was difficult to reproduce the gap between the ceiling system and the periphery walls and the local large strains caused by the contact between them. On the contrary, an actual ceiling system at a large auditorium revealed ceiling failures at about 0.7 g of the induced accelerations (Kawaguchi et al., 2018).

Nonstructural damage is commonly expressed via fragility functions. To establish such functions, we need data that characterizes the relationship between the external action and the degree of damage. As noted above, the acquisition of such data appears significantly more difficult for nonstructural elements than for major structural members, and accordingly, accumulating such data is hard to achieve.

It is here that SHM becomes very useful, as the authors have learned that it can provide precious data on nonstructural elements. Fortunately, and thanks to the generous assistance of the building owners, the authors had opportunities to closely examine nonstructural damage to 27 buildings shaken in the 2018 Osaka earthquake. Since the buildings were equipped with the SHM system, data on the interstory drifts and floor accelerations were available. Correlating the observed damage (by visual inspection conducted after the earthquake) with corresponding data on external action (estimated using the SHM data), we were able to develop fragility curves for some nonstructural elements (Kanda et al., 2021). By continuously accumulating such data from actual nonstructural responses and classifying them with respect to the element type, the connection method, and other controlling parameters, we will eventually be able to establish more reliable and comprehensive fragility curves, which are more specific to respective elements and their connections. O'Reilly et al. (2023) described a procedure to develop such curves using the monitored data.

What is important to note, however, is that the majority of nonstructural damage that is recorded and documented with SHM systems tends to be low to moderate damage, primarily impacting the building's functionality, with more critical limit states relating to life safety and complete loss tending not to be so well-documented. This is due to the infrequency of such levels of shaking in addition to the more concerning structural damage that would likely result in such situations. Hence, experimental testing in laboratories is still a crucial aspect to consider in order to fully characterize the damage to nonstructural elements across all damage states. However, potential pitfalls relating to appropriate and representative boundary conditions and the loading protocols adopted during experimental testing are issues that require careful consideration. Interested readers are referred to O'Reilly et al. (2023) for more in-depth discussion.

Pros and cons of "caution (Yellow)" in SHM assessment

> ***Opinion 3***: "*Caution (Yellow)*"*is a good message for building owners and managers with a solid contingency plan including readily available building maintenance workers and construction engineers. On the other hand,* "*Caution (Yellow)*"*tends to frighten building owners and managers when such a contingency plan is unavailable, discouraging them from installing SHM.*

Through interactions with owners and managers of the buildings equipped with the SHM system, we have reconfirmed that large corporations that manage many buildings have solid support systems that can respond promptly to earthquakes and other disaster events. Maintenance workers are stationed permanently in each building, and they continuously check the operation of the entire building, including its mechanical systems, electricity, gas, water, and other utilities. Furthermore, the building owners secure a permanent relationship (i.e. contracts) with construction firms that can come to the building promptly after any inconvenience and will prioritize addressing its problems.

As a recent example, one building equipped with the SHM system was shaken strongly late at night (11:30 pm) on a Saturday. The SHM system functioned and identified the building's status as "Caution (Yellow)," which was instantaneously transmitted to the building manager. Independently of the SHM information, the maintenance workers living close by gathered at the building within half an hour of the event and visually inspected the damage and operation conditions. On the following day (although it was Sunday), engineers from the contracted construction firm also arrived at the building and conducted a professional inspection.

To summarize, the building manager, who represented the building owner and was in charge of the building's maintenance, received information on the building's status from three independent sources. The first and most immediate information was from the SHM system; the second information was from the on-site maintenance workers who arrived at the building within an hour; and the third information was delivered within a day from the construction firm's engineers. The building manager collected the information from the three sources, confirmed the level of damage, and took necessary actions without losing time. In fact, the building was fully workable on the following Monday. Here, the assessment of "Caution (Yellow)" by SHM was deemed useful. First, the maintenance workers could go into the building (as there was no fear of collapse based on the diagnosis delivered by the SHM system) and check the damage and operation conditions. Second, the building manager requested the constructor to check the damage status to plan for possible repair work. On the contrary, if no SHM had been installed, it would have been hard for the maintenance workers to enter and check the building (because of the probable risk of injuries due to aftershocks), and it would have taken more time for the building manager to contact and coordinate with the construction firm.

This incident reminded the authors of their difficulties in persuading local governments and authorities that manage public buildings such as schools when talking with them about the SHM installation. They understood the benefit of SHM, but actual implementation has remained low until now. The initial cost is an impeding factor, but far more serious for them is the maintenance and particularly the course of action in case of serious events. With a limited workforce in the local government, they have difficulties allocating semi-permanent maintenance workers or securing local construction firms who can send engineers to the public buildings immediately after severe shaking. This significantly contrasts what we experienced with the private owners of instrumented buildings. Officers in local governments and authorities have a serious worry: Should "Caution (Yellow)" be announced, they may have very limited resources with which to respond. This shows us that "Caution (Yellow)" is nothing but a signal that may heighten worries without offering workable solutions in a timely manner. This appears to be a significant cause for hesitation regarding the SHM installation in the public sector. In such a case, a more straightforward classification, for instance, "Safe (Green)" and "Likely Safe—Inspection and verification required (maybe Vermilion)" may be more relevant. The threshold corresponding to this "Likely Safe" may lie somewhere between the existing thresholds for "Safe" and "Danger," which still gives some immediate instruction to occupants on what to do, but also underlines the importance of engineering inspection afterward. This new threshold would serve as a boundary that allows for some structural damage, provided that the building would be unlikely to collapse during aftershocks. If the response remains below this threshold, inhabitants would not need to evacuate the building immediately after the event. This has the double benefit of allowing occupants to clearly understand what to do, and to allow the limited resources of engineers to focus on inspecting more critical buildings first. Quantifying this new threshold value requires thorough investigation, and it remains a topic for further debate.

A key point should be noted when honest impressions and sentiments shared by the owners and managers of the monitored buildings were collected. When the monitoring service was started, a natural distance existed between the building owners/managers and the SHM operation team. To overcome this distance, an annual report was sent to them, listing the dates and magnitudes of shaking for each monitored building, along with comments on the degree of damage. Once significant shaking hit a monitored building, verbal communications were exchanged with the building managers about the severity of the damage, both structural and nonstructural, and the inconveniences encountered. If the damage was beyond minor, the building was typically visited within half a month, the damage was checked, and the managers' narratives were recorded. By repeating such exchanges, the distance was reduced significantly, and the owners' and managers' openness increased. Until now, much of this data has been accumulated through old-fashioned human interactions rather than modern sensors. Regarding building owners' willingness to share data, their initial attitudes after the installation of SHM tend to be cautious or apprehensive, primarily due to concerns about potential public reactions to data disclosure. However, these concerns typically diminish over time as the relationship between building owners/managers and the SHM team strengthens. Most building owners eventually become supportive of sharing their data, provided that it serves the public interest and their building names and addresses remain anonymous.

As noted above, the primary subject for communication has been to assure and characterize the degree of actual damage sustained by the SHM buildings, such as the levels of cracks of structural beams, columns, and walls, drops, cracks, and failures of various nonstructural elements (partition walls, ceilings, and window glasses), and disorder to utilities (water, electricity, gas, and others), among many. This situation infers that the most significant hurdle of the current SHM lies in difficulties/uncertainties in translating the response (estimated by SHM) to the actual damage. So far, the actual damage needs to be checked primarily by humans through their eyes, despite the emergence of many novel technologies. Adopting artificial intelligence (AI)-driven technologies is a likely solution to automate the actual damage (not the response) assessment and reduce human involvement. Still, it has yet to be ready for actual practice that must ensure robustness, reliability, and comprehensiveness.

Along this line, another argument is an effort to establish the contingency action plan and agreement between the building owners and design and construction firms so that professionals can assist the building owners and managers at the earliest recovery possible. A good example is the Building Occupancy Resumption Program (BORP) exercised in California in the United States (City and County of San Francisco, 2001) where near real-time monitoring instead of tagging has been implemented. The program offers the advantage of building owners retaining an engineer before a disaster with the end results being that re-occupancy time is lessened. This is achieved by reducing the time to inspection, and the time it takes an engineer to familiarize themselves with a building (Lang et al., 2018). In Japan, such an agreement has been formed commonly between the local and central governments and the construction industry, particularly for recovering public utilities (e.g. water and gas systems) and infrastructural systems (e.g. roads, bridges, and river banks). However, such an agreement is less formal and more market-driven for recovering buildings. Furthermore, we should recognize that in an emergency, the market balance between the supply and demand developed for peacetime is suddenly disturbed, and we encounter a severe shortage of the supply (i.e. those who rescue) relative to the demand (i.e. those who need to be rescued). Should such a situation occur, the suppliers, that is, design and construction firms, will provide their priority service to their best clients. Here, a market-driven attitude generally tends to prevail among the suppliers.

Summary and conclusions

This opinion article presents the authors' contention about the utilities of SHM based on their eight-year experience with the management of an SHM system. The authors have acquired many lessons from the management, and this article focuses on the authors' opinions about the utilities of "Caution (Yellow)" tag as they are deemed most relevant to the promotion of market-based SHM. Major remarks of this article are as follows:

1. An outline and experience obtained from the 8-year management of an SHM system was summarized. As of December 2023, 553 buildings have been equipped with the SHM system, including 133 relatively old buildings (over 40 years). A total of 24,944 records were obtained from the buildings equipped with the SHM system. Most of them are small, not greater than 1 m/s^2, in the maximum acceleration at the base floor (approximately 0.1 g). Still, 115 records go beyond 1 m/s^2 at the base floor, with a few records arriving at as much as 3.3 m/s^2 (0.3 g). The corresponding accelerations at the top floor also reach nearly 1.0 g.
2. The damage criteria: "Safe (Green)," "Caution (Yellow)," and "Danger (Red)," are dynamic and can be updated based on past experience. It is notable that the SHM system can enhance its knowledge with time by accumulating the response data.
3. SHM is one of the best means to generalize fragility curves of nonstructural elements, all the while "Caution (Yellow)" has inherent relevance to the nonstructural damage. This is primarily because the behavior and performance of nonstructural elements are difficult to reproduce in the laboratory, given that the connections and specific details tend to play a significant role.
4. "Caution (Yellow)" is effective, but it is primarily for those building owners and managers who have a solid contingency plan, supported by on-site maintenance workers and by readily available construction engineers. For those who do not have such support, "Caution (Yellow)" is more of a frustration or added problem to them for which they have no means to take effective action.

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