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Development of the structural damage monitoring system using "Buckling-restrained brace with built-in displacement sensor"

T. NISHIZAWA(1), T. NORO(2), M. YOSHIZAWA(3), R. KOGA(4), K. SASAO(5), J. TOBITA(6)

(1) *Associate, NIKKEN SEKKEI LTD. Structural Engineering Section, Dr. Eng., nishizawa@nikken.jp*
(2) *Senior Manager, NIPPON STEEL & SUMIKIN ENGNEERING CO., LTD., noro.tadayuki.64t@eng.nssmc.com*
(3) *Partner, NIKKEN SEKKEI LTD. Structural Engineering Section, Dr. Eng., yoshizawa@nikken.jp*
(4) *Senior Manager, NIPPON STEEL & SUMIKIN ENGNEERING CO., LTD., koga.ryuuji.eq2@eng.nssmc.com*
(5) *Senior Manager, NS Solutions Corporation, sasao.kazuhiro.2b3@jp.nssol.nssmc.com*
(6) *Prof., Disaster Management Office, Nagoya Univ., Dr. Eng., tobita@sharaku.nuac.nagoya-u.ac.jp*

Abstract

During the Great East Japan Earthquake, in areas 400 to 500 km from the epicenter with Japanese seismic intensity of 3, skyscrapers swayed greatly making the people inside anxious, and afterwards there were cases where judgment regarding the continued use of the building was requested. Since then, there have been increasing activities to utilize monitoring of skyscrapers for judgments of whether or not such buildings can continue to be used.

However, currently the number of owners of skyscrapers who perform monitoring is still small. The biggest reason for this is the high cost of installing the monitoring equipment and taking continuous measurements.

In addition, monitoring technology is still evolving. At the current time, the prevalent level of measuring systems is only monitoring using acceleration sensors, but when using this measuring method on skyscrapers where bending deformation is large, there is a technical problem in that it is difficult to measure the inter-story deformation component which has high correlation with damage since the horizontal displacement component due to the twist angle is measured regardless of whether any inter-story displacement has occurred in the upper stories.

The new system for monitoring the degree of structural damage proposed in this paper is monitoring with devices integrating buckling restrained braces as damping members. The system is inexpensive since it involves only the addition of small measuring devices to the damping members that are required by the plan. It then becomes easy to directly grasp the inter-story deformation component by measuring the displacement of the braces. The damping braces themselves are locations for large displacements, so there is no need to go to the trouble of searching for places with large displacements in order to deploy sensors for the monitoring plan.

Since a system in which measurement data can be transferred via the internet and collected in a data center can be constructed, enabling central management of building data, there is no need for a data-collection system in each building, and in the event of a major earthquake, information on the damage over a wide area can also be handled. Not only can the degree of damage to a building be determined, the residual seismic performance of damping members can also be judged. In this way, the proposed monitoring system has many advantages, and it can be expected to become a new technology for spreading structural monitoring.

Furthermore, this paper also discusses that the proposed monitoring technology is at the stage of practical application based on testing of components of the proposed measuring devices and analysis results from installation in an actual building.

Keywords: Structural health monitoring, Buckling-restrained brace, Mega earthquake

1. Introduction

Currently in Japan, there is growing momentum to use structural health monitoring to grasp the degree of damage of a building after an earthquake. The importance of using measurement results as the basis for judgments related to the safety of a building in order to continue to use a building immediately after an earthquake is beginning to be strongly recognized.[1] Also, the number of designers and contractors who propose the installation of at least seismometers to owners when constructing a new skyscraper is increasing. Further, there is a movement to utilize structural monitoring for the purpose of reducing the environmental load of construction.[2] When reusing structural members of dismantled buildings in the construction of new buildings, one issue is whether or not those structural members have suffered major loads in their history and have sufficient performance for use as members for a new building. To solve such an issue, research is being conducted to install sensors that can record the load history of the member to clarify its performance as a new structural member and the structural performance of the building can be secured.

Currently, for structural health monitoring in building construction, there are systems in which seismometers (accelerometers and speedometers) are installed and building damage is roughly determined from the building floor response values[3]and systems which measure the distortion of the framework to identify damage positions in more detail or judge the degree of damage of structural members [e. g. [4]~[6]]. Of these, currently only the system that uses seismometers to roughly determine the degree of damage can be said to be at the practical level in the sense of actually being widely employed in buildings. However, it is thought that the damage degree judgment accuracy of this kind of system using seismometers is insufficient.

For skyscrapers where bending deformation is large, there is a technical problem with this kind of system using seismometers in that it is difficult to measure the inter-story deformation component which has high correlation with damage since the horizontal displacement component due to the twist angle is measured regardless of whether any inter-story displacement has occurred in the upper stories. For this reason, although evaluation using analysis models at the time of design is required, the analysis models at the time of design that become the base for comparison are generally vibration analysis models at the time of design that have not been adjusted to be consistent with actual building behavior and do not take into consideration the actual building vibration properties due to changes in the loads after completion and changes due to the passage of time. Because of this, vibration analysis models slightly different from the actual vibration properties are used for consideration, making the judgment accuracy poor.

In addition, the most likely structural damage for steel-frame skyscrapers is fracturing of the lower flange of the steel girders, and in such case since the historically absorbed energy of the girders is greatly reduced, it is major damage and the building should be judged as unsuitable for continued use after the earthquake, but even if the focus was placed on the changes in dynamic properties based on the measurement results from seismometers before and after the earthquake, the changes in the natural period, etc. are slight[4], making it difficult to suitably estimate the structural damage.

As a method for more accurately detecting the damage than this kind of system using seismometers, there is a system that measures the distortion of the structural frame and attempts to more finely identify damage locations or the degree of damage of members. With this system, although it is ideal to measure as many members as possible, it is currently economically difficult to measure many members and there is also the hassle of installing sensors and running wires in the midst of construction, so it can be considered as remaining at the research level.

The technology to solve the above problems proposed in this paper is a sensor-integrated buckling restrained brace. If sensors could be installed on the damping members such as buckling restrained braces, etc. that themselves bear relatively large forces in the design of a building, then it becomes possible to select the members which can be expected to yield at an early stage as measurement subjects without having to perform any special investigation, and since it can be accomplished by just adding sensors to structurally necessary damping members with minimum jigs needed for measurement, it can be expected to have the effect of reducing costs. Furthermore, if a system that can collect data without being a hindrance to management during and after construction can be made, then it can be easier to introduce such a measurement system and it becomes a system that has the potential of spreading to common use.

2. Measurement method

2.1 Overview of measurement method

Fig.1 shows a comparison of the proposed measurement method with the system using seismometers currently in common use in Japan. The figure shows from the monitoring device design to installation in the field, and the work from when an earthquake occurs until judgment of the degree of damage is classified into the work that occurs at the construction site and the work done at a desk. Then for these kinds of work, the advantages *1 to *8 of the proposed method over the common methods are indicated.

As an advantage at design time, *1 can be listed. For judgment of the degree of building damage, it is desirable to install strain sensors in many locations on the structural framework, but the cost would be large and it is not realistic. Therefore, it is necessary to select from among the numerous structural members those members that would probably yield at an early stage according to analytical studies. Performing such selection requires a great deal of effort. On the other hand, in the proposed method the sensors are installed on damping members called BRB, which by their very nature are automatically places where yield will occur at an early stage. Because of this, when planning installation locations, it is sufficient to only decide on how dense the sensor installation should be, and there is no need to perform special investigations for sensor layout.

As advantages at the time of construction, the first one is *2, the fact that sensors can be installed at the factory. Since the proposed product is integrated together with factory-produced damping members, a point of excellence is that high-accuracy installation during factory assembly becomes possible. A further advantage is *3, that the factory-produced parts just need to be installed and there is almost no sensor installation work, so that it does not hinder construction in any way. In common systems, in addition to the measuring devices, equipment to collect and display measurement information is also required, making it necessary to investigate where to install the equipment and perform a lot of on-site work such as explaining how to handle the equipment. The proposed system has the advantage of *4, comprising a system in which the measurement data is uploaded via the internet. Although this kind of activity could be done with common systems, it has not actually spread much and usually data is stored on equipment installed on-site and then the data is taken from the site.

The advantage from the start of service after building completion is *5, that the risk of sensor failure being left unrepaired is low. In common systems, since until now sensor installation was completed on location, sensor failures were ignored and problems with sensors not working properly during earthquakes occurred. In the proposed system, since signals indicating the health of the sensor are periodically sent to the data server, the risk of sensor failure being ignored is reduced.

When an earthquake occurs, the effects can be handled with little loss of time based on the data which is automatically sent. Engineers can begin investigations based on the received data, and because of advantage *6, the data values having high correlation with building damage by being values that almost directly measure the inter-story deformation angle, judgment of the degree of damage can be performed smoothly. In common systems, even if the skyscraper has bending deformation and the upper stories of the building twist rigidly, it ends up being judged as each story having horizontal displacement, and in addition in many cases seismometers themselves are not installed on each story, so that analytical considerations become essential and because of this, delays in the judgment of the degree of damage occur.

Furthermore, the proposed system also has advantage *7, the potential to add a primitive mechanism to enable visual judgments. Using this, the on-site building manager can visually judge the degree of inter-story deformation that has occurred in the building, so that even if by some chance the system fails, the degree of damage can be judged, although accuracy is reduced. From the above features, the proposed system is a system with advantage *8, the ability to enable rapid, high-accuracy judgments of the degree of damage.

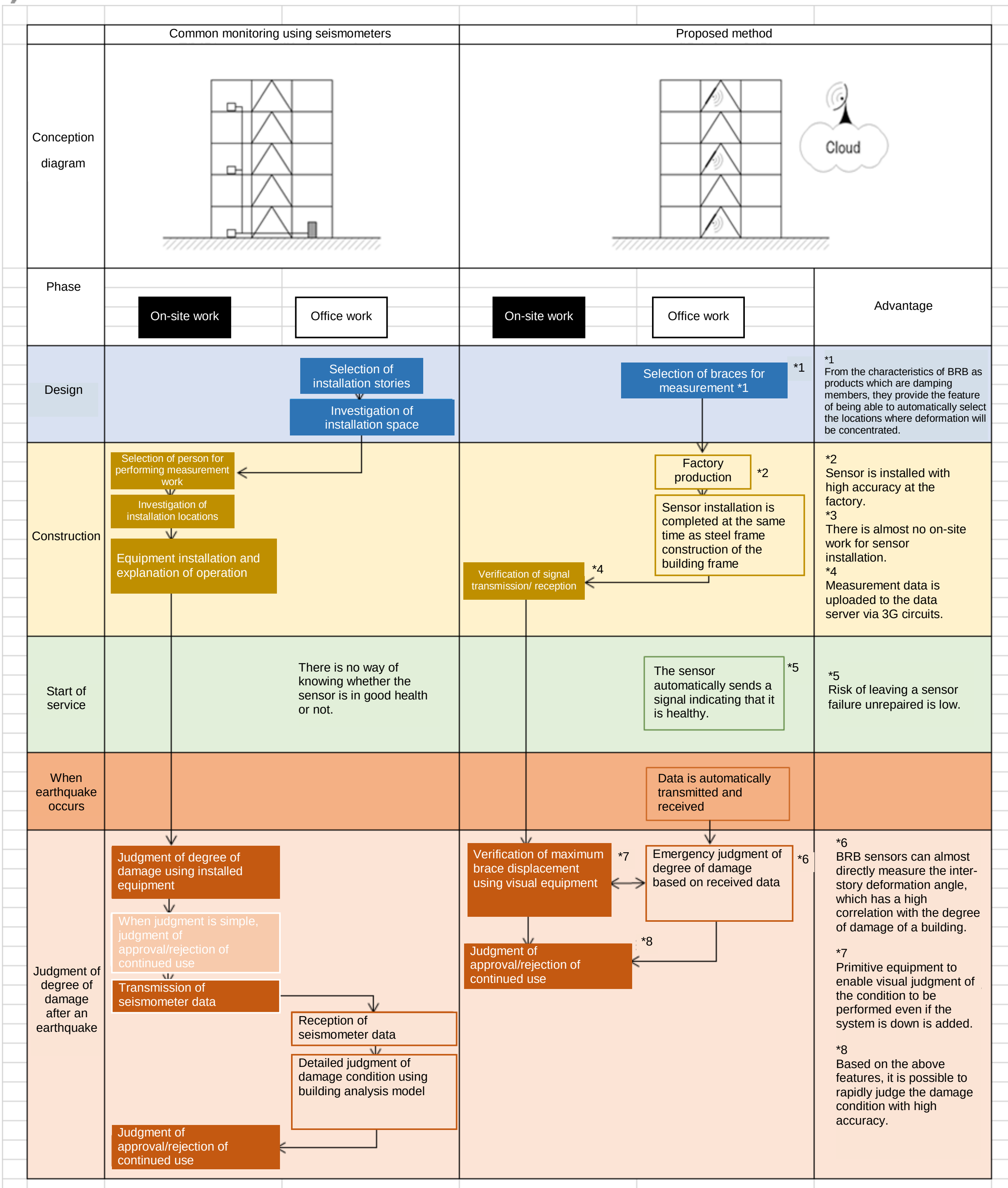


Fig. 1 – Comparison of proposed monitoring system vs. conventional monitoring methods

2.2 Overview of sensor

The sensor used by the proposed method was developed as a device to be integrated into a buckling restrained brace and produced in factories, and it is thought that it would be installed in newly constructed buildings in many cases, but it could also be added to buckling restrained braces in existing buildings.

A buckling restrained brace is different from common braces in that buckling is suppressed so that even after the brace core material has become plasticized, it can stably absorb large amounts of hysteretic energy, and it is often used as a damping member. There are already many examples where it is employed in steel-frame buildings including skyscrapers. Nippon Steel & Sumitomo Metal Corporation, which is a group company of the writers [(2) (4) (5)], was the first company in the world to develop a buckling restrained brace called an "unbonded brace".

The sensor installed on the buckling restrained brace (hereinafter abbreviated as "BRB sensor") consists of a displacement sensor to measure the extension and contraction of the unbonded brace, a detection sensor to start up the sensor, and a transmission system for transmitting data. The UBB sensor body is a battery system. The configuration of the BRB sensor is shown in the figure below.

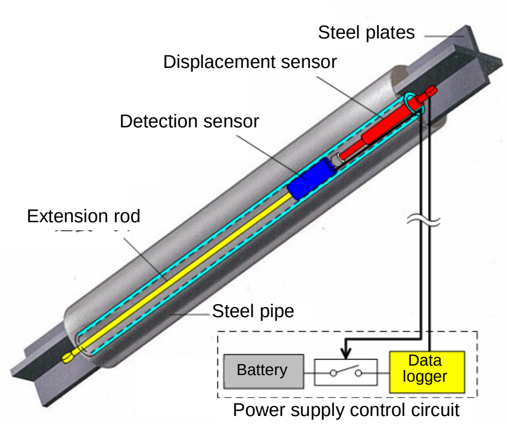


Fig. 2 – BRB sensor configuration

(1) Detection sensor

In order to suppress power consumption, the system has a mechanism to switch on the data logger when the displacement sensor part has reached an axial displacement of ±2mm along the unbonded brace and to then switch it off automatically 600 seconds after the start of measurement. In addition, when earthquakes continue, the equipment will restart measurement.

(2) Displacement sensor

The axial displacement of the unbonded brace is measured at 20-ms intervals using a potentiometer. The specifications this time are maximum displacement of ±50mm, measurement error within ±0.5mm, and durability for 5 million reciprocation cycles. Also, the usage temperature range is -25 to +85°C.

(3) Data logger and transmitter

There are two functions: Data transmission and data storage. The data transmission function will be explained later. For data storage, internal memory (microSD) is provided.

2.3 Experiments to verify sensor operation

Experiments to verify BRB sensor operation in actual applications were conducted. In the experiments, the focus was on the trigger function and verifying measurement accuracy. This experiment used an actual-size unbonded brace, and the UBB sensor was installed inside the buckling-restrained pipe of the unbonded brace. In order to measure the amount of core member extension and contraction, the BRB sensor was extended to both ends of the core member. Also, in order to verify the measurement accuracy of the BRB sensor, a differential-transformer-type displacement sensor was installed separately on the outside of the unbonded brace. The pictures below show the experiment setup. Sinusoidal waves and irregular waves to provide displacements of ±50mm were applied to the unbonded brace.

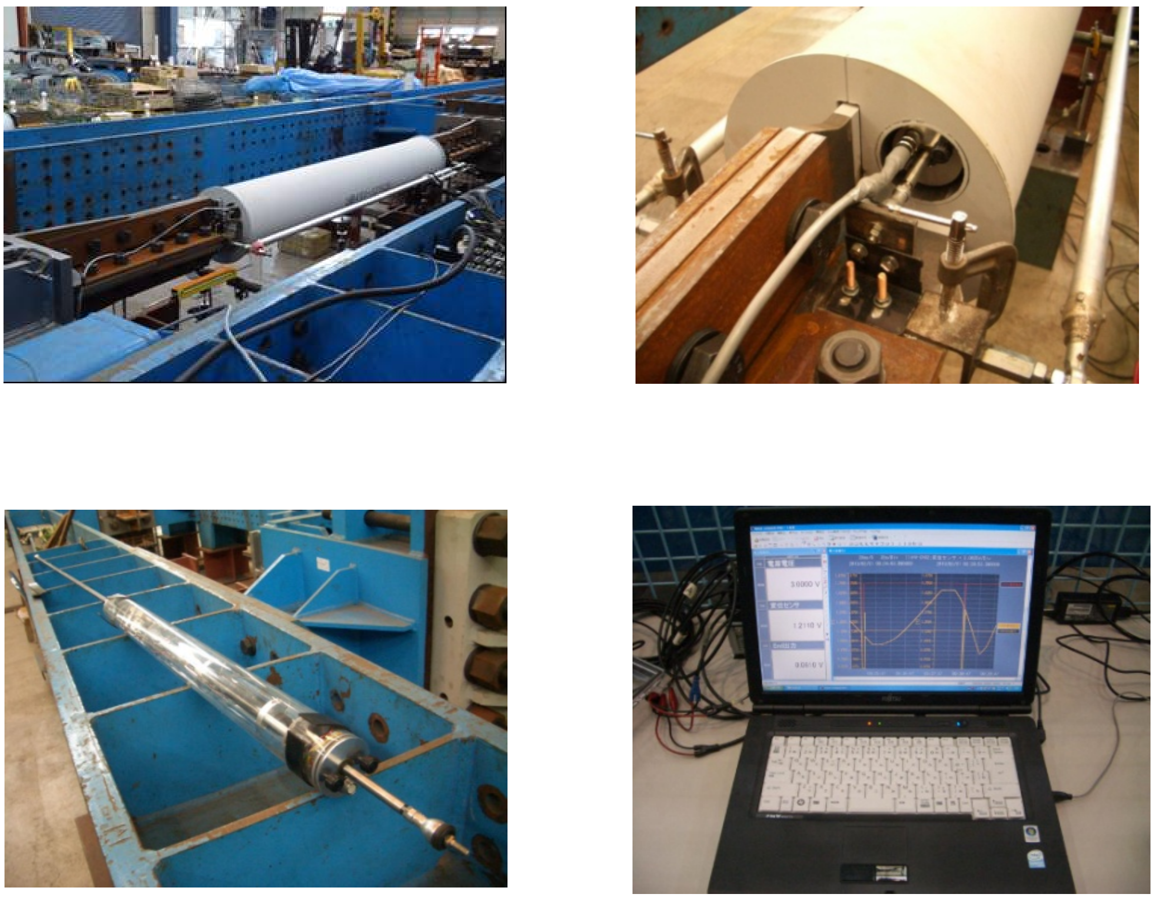


Fig. 3 – BRB sensor operation confirmation experiment setup

(1) Measurement accuracy

The extension/contraction measurement results for the measured values of the BRB sensor and differential transformer type measuring equipment are shown below. Both the BRB sensor and differential transformer type measuring equipment provided the same measurement values, and thus the same measurement accuracy.

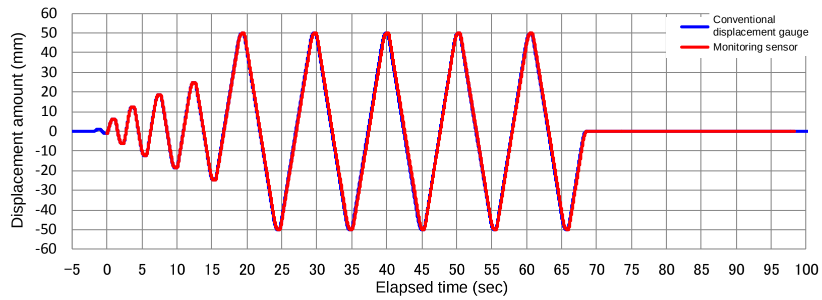


Fig. 4 – Measurement results (Comparison of BRB sensor and differential transformer type sensor)

(2) Trigger

The BRB sensor used in the experiment was set to automatically switched off power 600 seconds after trigger operation, and after that, to restart measurements 1.5 seconds after the trigger was operated again (assuming a situation in which vibrations such as from earthquake vibrations continued for a long time). The upper figure below shows the automatic stop condition and the lower figure shows the condition when restarting measurement. It can be seen in both cases that the extension and contraction displacement of the unbonded brace were measured according to the set conditions.

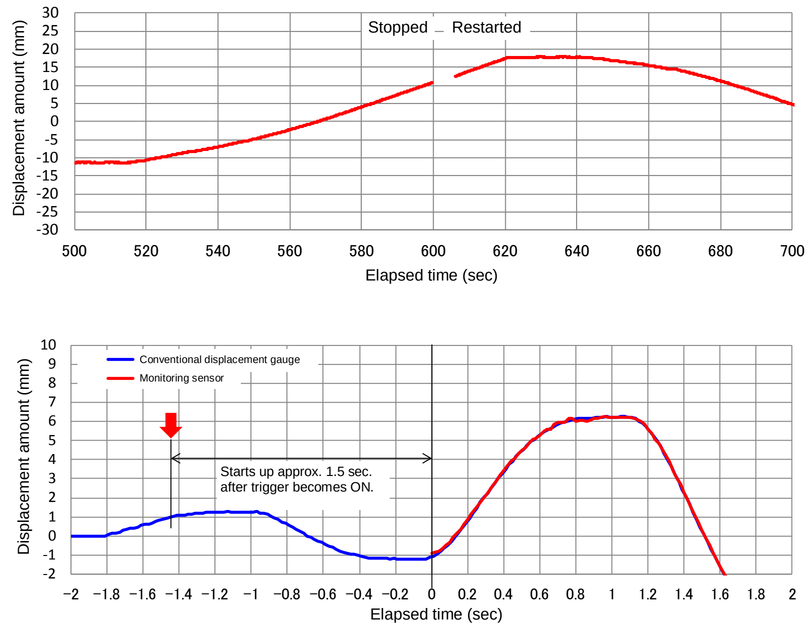


Fig. 5 – Measurement results when restarting measurements by trigger operation, etc.

2.4 Overview of data transfer system

(1) Transfer section

The transfer section consists of a part to transfer measurement data to a relay station inside the building and a part to transfer the data from the building to a cloud server. Since a wireless LAN is often installed inside a building, an empty channel in the same band is determined ahead of time so that the measurement data radio waves do not interfere with the wireless LAN channels in use, and a sensor network using ZigBee is constructed. When there are no obstacles to line of sight, a ZigBee Fresnel zone of approx. 100m can be secured, but inside a building, it is standard to set up relay stations approx. every 50m because of the presence of walls, partitions, etc. In addition, as preparations for power outages, each relay station is equipped with a battery backup system.

(2) Accumulation section

Data accumulation is performed from the time when the displacement detection part detects a certain amount of displacement until the variations in displacement have settled down. During data accumulation, sampling is performed every 50ms. The data is accumulated in the microSD card of the accumulation section, and is also transmitted in real time via the sensor network. In addition, in order to verify the health of the equipment, the health information is also transmitted every 3 hours via the sensor network.

(3) Sensor network and cloud

In order to have a mesh network resistant to network damage, ZigBee was selected. For the protocol, DigiMesh from Digi Co. is used. This method can automatically reconstruct connection routes.

The data is transferred via the sensor network to relay stations that can access 3G circuits, and from there the data is uploaded into the cloud. For the cloud, Windows Azure is used.

Furthermore, since it can be expected that in the case of an earthquake it might not be possible to perform data communication via 3G circuits, the system is programmed so that if communication is not possible, measurement data will be continually stored in the microSD card of the accumulation section, and when communication is restored the stored data will then be retransmitted.

3. Measurement results and their evaluation

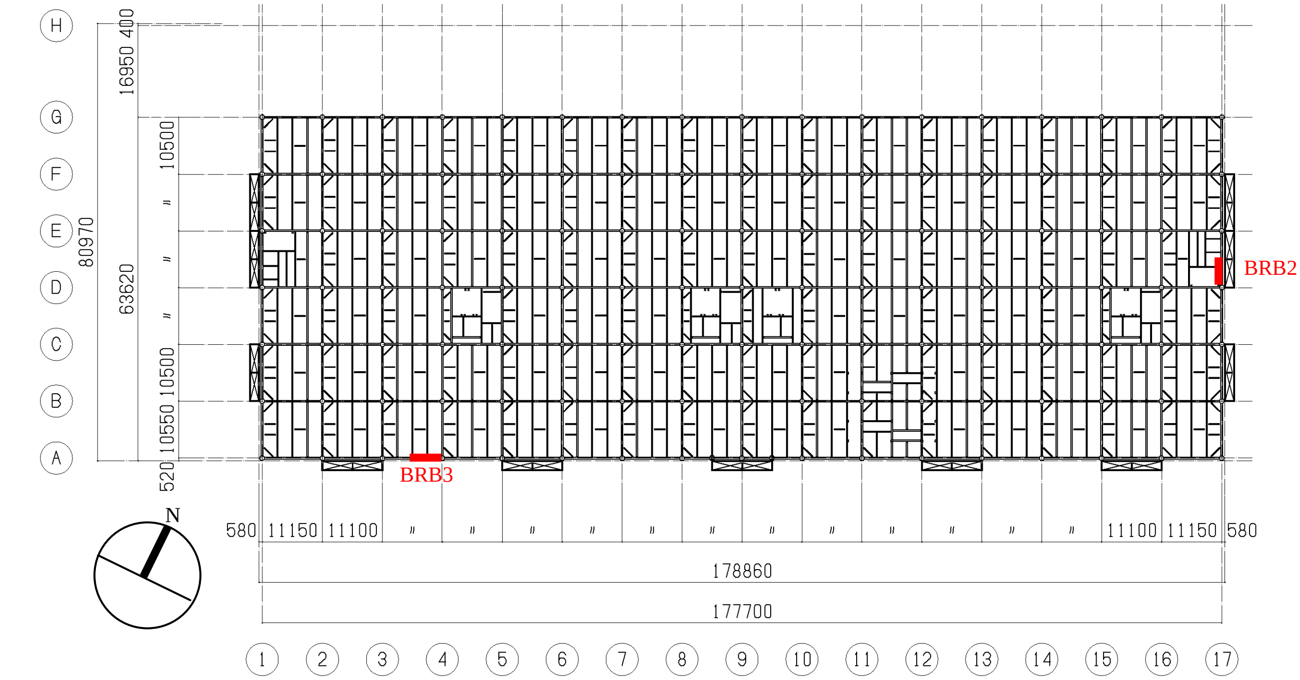
3.1 Example of application in an actual building

The proposed measurement system has already been installed as a trial application in an actual building. In this section we will give an overview of the installation in an actual building and discuss the usefulness of the proposed system from analysis results based on earthquake records.

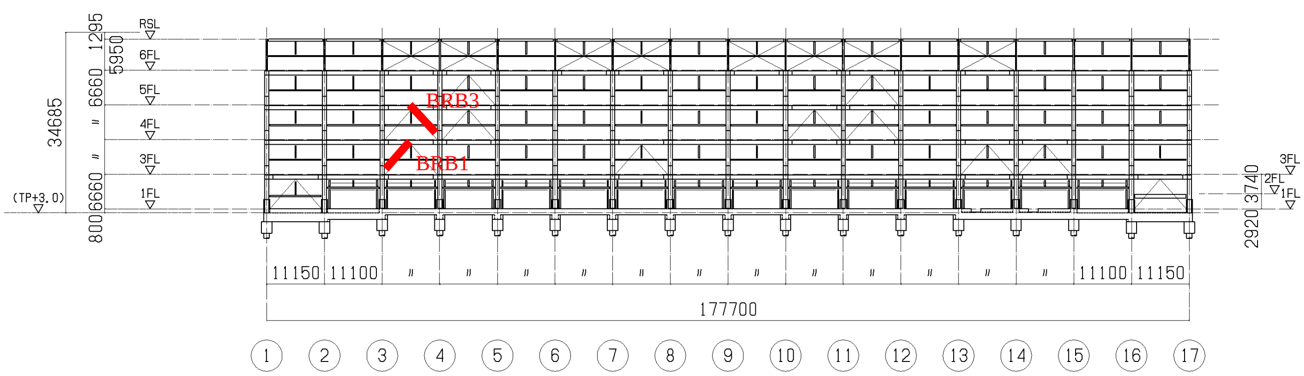
An overview of the actual building in which the system was installed is shown in Table 1 and a typical framing plan and framing elevation are shown.

Table 1 – Overview of measurement example building

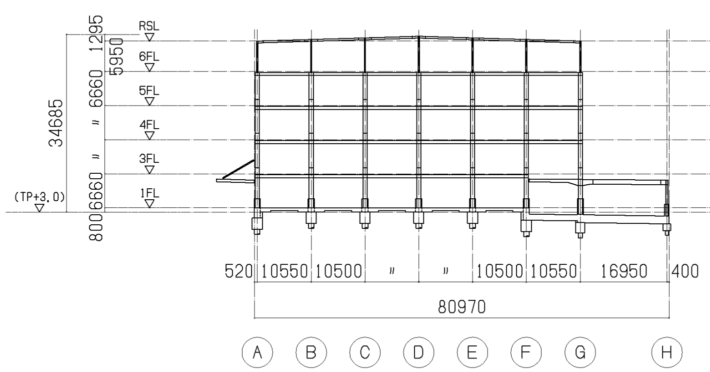
Application: Warehouse engaged in warehousing operations	Number of stories: 6 above-ground stories	
Total floor area: 63,108.60m^2	Building area: 17,222.82m^2	Eave height: 33.4m
Structure type: Steel-frame structure (pillar CFT structure)	Foundation work: Pile foundation (Steel piles$\varnothing$600 to $\varnothing$1000	Structure format: Rahmen structure combined with buckling restrained braces (in both X and Y directions)



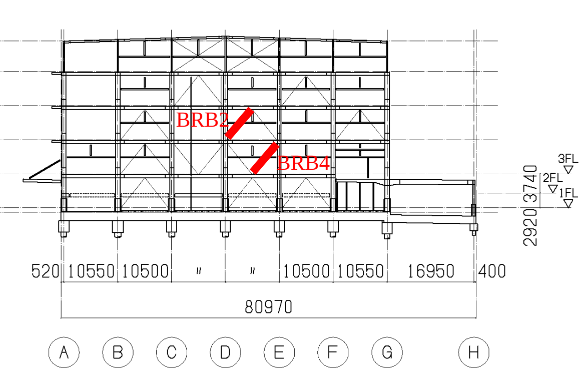
Standard floor framing plan (4th Floor)



Axis A framing elevation



14th axis framing elevation



16th axis framing elevation

BRB1 : BRB sensor locations and No.

Fig. 6 –Building where system was installed

For trial application in an existing building, add-on type sensors were installed on existing buckling restrained braces. The installation were a total of 4 buckling restrained braces as indicated on the 3rd story and 4th story plan drawings, measurements were taken in the X and Y directions on these two stories, and for the building which was in use as a warehouse, the emphasis was placed on low loads which could easily reach the sensors. Further, although the goal was to be able to perform damage degree monitoring using only BRB sensors, in the trial application as a way to confirm the behavior of the BRB sensors, seismometers were installed on the 1st, 3rd, and 4th stories.

3.2 BRB sensor measurement status

After installing the sensors in an actual building as a trial, data transmission system improvements, etc. were performed repeatedly to arrive at the current system. Currently, the BRB sensor continually sends notification of the sensor health every 3 hours so that the proposed system can be considered to be operating healthily.

Regarding earthquake recording, after installing the BRB sensors, regrettably no earthquakes large enough for the sensors to react to have been measured. On the other hand, small earthquakes at levels to which the BRB sensors did not react were recorded by the seismometers. In such cases, although it is a paradoxical explanation, through studies based on analysis of the building for such earthquake records, by explaining that there were earthquakes at levels to which the BRB sensors did not react, we will explain that the BRB sensors are operating normally. The detailed explanation is in the following section.

Of the earthquakes recorded after installation of the sensors, the largest was an earthquake offshore from Ogasawara on May 30, 2015 and the acceleration waveform recorded by the seismometers for earthquake is shown in Fig. 7.

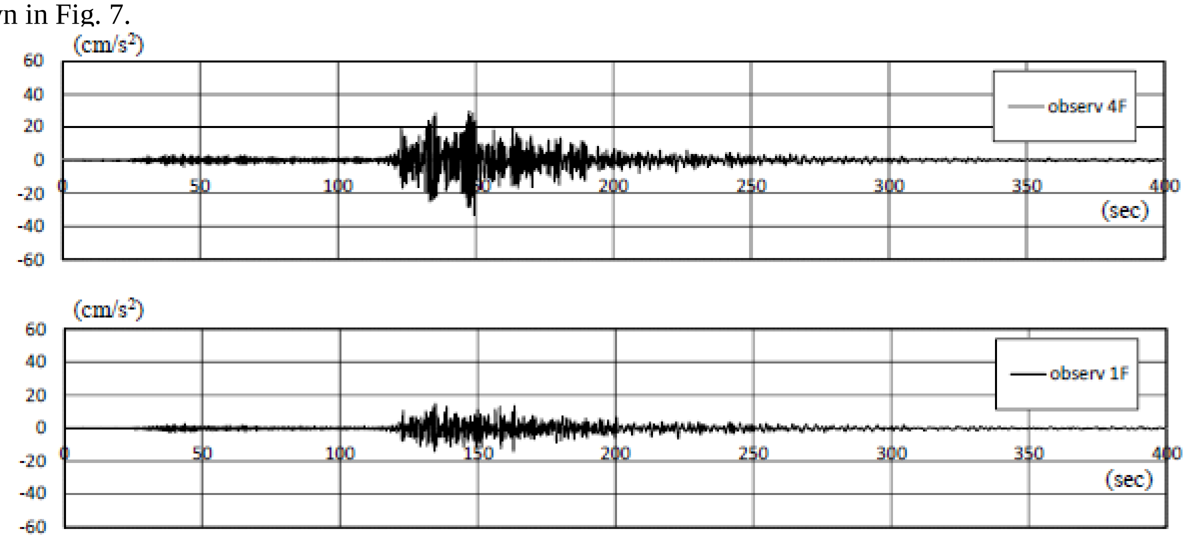


Fig. 7 – Earthquake records recorded by seismometers for each story of the building

(2015.5.30 OGASAWARA-OKI EW)

3.3 Evaluation of BRB sensor behavior based on structural analysis

The 3-dimensional spatial frame model was used as the structural analysis model. The actual building was faithfully modeled in the spatial frame model with the BRB as wires that deform in the axial direction, and it was possible to directly calculate the BRB axial direction displacement at the time of an earthquake using analysis. The floor of each story was modeled as a rigid floor, and masses were arranged as being at the center of gravity of each story.

In the structural analysis model, modeling is performed taking into consideration the actual conditions of the fixed loads and live loads so that the model's vibration characteristics are consistent with the actual building, and FFT analysis results using earthquake records are used to perform fine-tuning. Specifically, fine-tuning by increasing girder rigidity was performed so that the building's primary natural period was roughly matched. This adjustment can be said to take into consideration that non-structural members attached to major girders had the effect of increasing girder rigidity at the time of small earthquakes. Table x summarizes the comparison of the translated primary natural period of the building based on analysis of earthquake records with the analysis results.

From the table, the analysis model and the roughly translated primary natural period of the actual building match and it can be presumed that a suitable model was achieved.

Table 2 – Comparison of the natural periods of the actual building and the analysis model

Period (sec)	Translated primary EW direction	Translated primary NS direction	Twist
FFT results from earthquake records OGSAWARA-OKI 2015.5.30	0.72	0.71	—
Analysis results	0.74	0.76	0.66

Fig. 8 shows the acceleration records from the seismometer installed on the 1st story of the building as shown in the previous section and the results of dynamic analysis when they were input to the analysis model. The response acceleration results for the node near the installed seismometer on the 4th story roughly matches the actual building, and it can be seen that the analysis represents the actual building to a certain extent.

The response axial displacement of the BRB sensor on the 4th story is shown in Fig. 9. From the figure, it can be seen that the maximum value for BRB axial displacement was around 2 mm, and it is expected that it did not reach the trigger level of 2 mm. On the other hand, the sensor continued to send the signal indicating its degree of health before and after the earthquake. From the above results, although it is paradoxical, it can be considered that the sensor was operating normally.

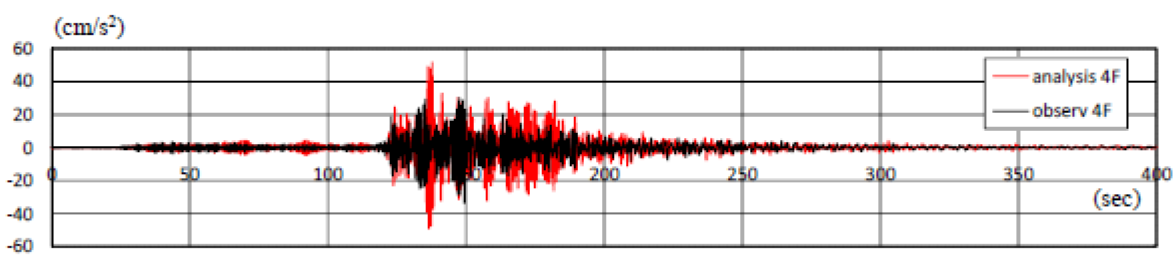


Fig. 8 – Comparison of seismic response analysis results and monitoring results (4th story location)

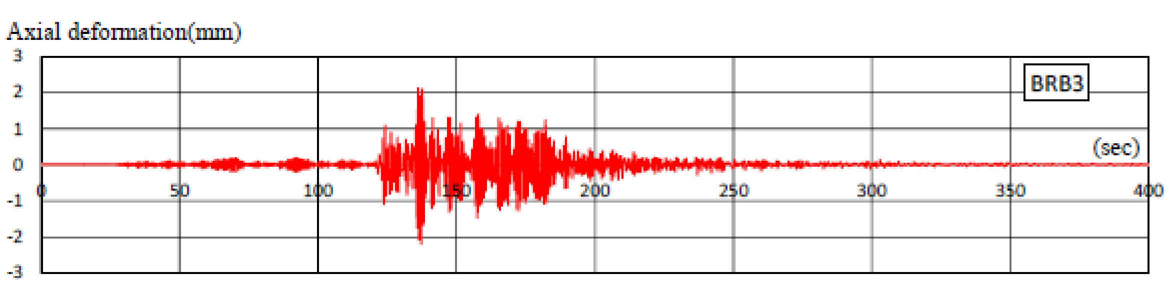


Fig. 9 – BRB sensor seismic response axial displacement waveform

4. Conclusion

The proposed system is sensors integrated with the BRB used as damping members, and has the advantage of being able to almost directly measure the inter-story deformation which has high correlation with the degree of building damage. From the characteristics of a BRB as a damping member, they are automatically selected as the locations within the structural framework where stress is concentrated and which yields at an early stage, and so for sensor installation, it is sufficient to only select on which BRBs to install the sensors and there is no need to spend time on the work of selecting which structural members will yield at an early stage as installation locations. In addition, the system also functions to monitor the BRB themselves, so that judgments regarding appropriate replacement timing can be made.

In this way, the choice of the brace to install BRB sensor is easy. However, some attention is necessary for the choice of the brace for the building which does a big torsional response. This is because inter-story deformation occurs because of the torsion so that we cannot measure the inter story deformation of outside frame appropriately when we measure only the brace of the core. Therefore, in the case of these buildings, it is necessary choosing the brace of outside frame as a measurement brace or to calculate the ratio of the core brace deformation and the outside frame deformation by analysis.

It was seen that the BRB sensor developed from the results of member behavior verification experiments can measure with the same practical accuracy as the highly reliable differential transformer type displacement sensor. In addition, the system has been applied to an actual building on a trial basis, and based on the status of the data transfer system and server equipment as well as the fact that the sensor continued to send signals indicating its health, it can be said that the system is already at the stage for practical use.

Unfortunately, earthquake records have not yet been recorded, and studies of future earthquake records are expected. Currently, installation in a skyscraper which was the original goal is being investigated.

As explained in Section 2, the system possesses many advantages over the commonly popular method of monitoring using seismometers, and it can be considered to be an excellent system which is economical, makes installation investigations easy, and enables rapid, high-accuracy judgments of the degree of damage.

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