Implementation of Real-time Seismic Diagnostic System on Emergency Management Center Buildings: In Case of the 2018 Osaka earthquake

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***Abstract*— Currently in Japan, a field survey by building experts is required to determine whether earthquake-afflicted buildings can continue to be used after an earthquake, so that official decisions on national and municipal-level assistance cannot be made without the completed survey results. Authors plan to introduce an automated real time seismic diagnostic system to the disaster prevention centers. This system consists of the seismometers installed in the building and observation data are saved in Internet clouds. Immediately after the earthquake, the system performs a simple diagnosis on the residual seismic performance of the building and notifies the results by e-mail. The MDOF lumped-mass model for use in the simple diagnosis is assumed to have normal tri-linear hysteretic characteristics at each story, using constants determined by referring to the analytical 3D frame model. This paper explains the proposed system and introduces the results of trial operation to the actual city hall buildings at the 2018 Osaka earthquake. After the Osaka Earthquake, the system was able to notify disaster prevention officials at the city hall of the results of the simple diagnosis within two minutes after the earthquake ended.**

***Index Terms*—Disaster prevention centers, Monitoring, Real time, Internet, Social implementation**

I. Introduction

In an earthquake disaster that covers a wide region as in the 2011 Great East Japan Earthquake, the damaged condition of emergency management center buildings in the quake-stricken area remains unknown for some time after the event. This poses a problem for national- and municipal-level emergency planning, since central facilities have to be designated in order to effectively provide emergency assistance. In this study, emergency management center buildings include government offices, which act as command centers for local emergency response; fire stations, which issue instructions to rescue and transport disaster victims; and hospital facilities, which handle the care and medical treatment of the sick and wounded.

Currently, a field survey by building experts is required to determine whether earthquake-afflicted buildings can continue to be used after an earthquake, so that official decisions on national and municipal-level assistance cannot be made without the completed survey results. However, the initial response survey relies heavily on specialist staff from surrounding municipalities and is frequently not implemented until several days after the event, since specialists living in disaster-struck areas are also victims themselves [1]. In the meantime, operations are carried out based on decisions of administrators who are not necessarily building experts. In one case during the Kumamoto Earthquakes, inpatients were evacuated from a hospital facility because parts of the ceiling fell off along with other superficial damages, but it was found out in a later survey that major structural members did not get damaged. To minimize the damage and confusion during catastrophic events over a wide region, a framework is needed to rapidly and accurately identify local disaster information (in this case, the damaged condition and advisability of continuing use of emergency management center building clusters), provide scientific data supporting the assessment of post-earthquake continued use of buildings to non-specialist administrators in charge, and convey the relevant information to stakeholders involved in disaster area recovery, as necessary.

In preparation for an expected major earthquake in the Nankai Trough, we have been carrying out studies for a program to introduce a real-time seismic diagnostic system on emergency management center building clusters in the Higashi Mikawa region in Japan. The system involves installing seismometers in buildings under study and storing tremor observation records continuously in the cloud in real time. After a disaster, the earthquake ground motion portion is automatically separated and sampled from the record, and authorities responsible for emergency management is notified by email of the results of damage assessment and residual seismic performance evaluation of the concerned buildings performed using numerical analysis models. In this paper, we describe our proposed system and present the results of trial operations conducted in municipal government office buildings as a test case at the 2018 Osaka earthquake [2] prior to actual system implementation.

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II. REAL-TIME SEISMIC DIAGNOSTIC SYSTEM

Fig. 1 shows the schematic diagram of the real-time seismic diagnostic system operations proposed in this paper. The real-time seismic diagnostic system consists of LAN seismometers that constantly take vibration response observations, a vibration data recorder and the automated seismic diagnosis system. The LAN seismometers and data recorder are inside the building and observation records are intermittently uploaded to the cloud on the Internet. The automated seismic diagnosis system have three stages: identification and sampling of seismic records, first-stage seismic diagnosis (Primary Seismic Evaluation) and second-stage seismic diagnosis (Secondary Seismic Evaluation). The first-stage diagnosis – a simple assessment of the level of building damage – simply assesses the degree of damage with an earthquake response analysis using a multi-degree-of-freedom (MDOF) lumped-mass model. If there is a possibility of building damage exceeding a certain level, the second-stage diagnosis is performed to get a more detailed evaluation. In this study, the degree of damage in each member making up the building is evaluated by a detailed time history response analysis using a three-dimensional (3D) frame model.

Previous studies on automated seismic diagnosis (or health monitoring) of buildings using seismometers assume installation of multiple seismometers in the building in order to detect damage accurately without the need to use numerical analysis models of buildings, which may be difficult for people who are not building professionals or engineers [3]-[5]. It was hoped that this will help promote the widespread use of the technology, but the downside is that a large number of seismometers will have to be installed as the size of the building gets larger [4]. Moreover, although it can estimate which story (or floor) in the building is damaged, the technology cannot be expected to provide a more specific evaluation of which parts and how the concerned story was damaged and to allow building administrators who are non-specialists to be entrusted with checking actual conditions.

However, unlike typical buildings, some emergency management center buildings have their numerical analysis models prepared and their time history response analyses conducted sometime during design, even when the buildings are less than 60 m high. With this in mind, we propose a seismic diagnostic system that aims to identify the specific building parts that are damaged, subject to the condition that the numerical analysis model of the building will be used. The objective is to help officials in emergency management facilities to determine whether emergency management center buildings, which are expected to function as hubs for recovery activities in disaster areas immediately after the event, can continue to be used without undergoing a building survey by experts.

The system uses a combination of Ruby and Fortran programming languages. Ruby handles the backbone of the system (i.e., overall system progress tracking, seismic wave sampling, run command of the first- and second-stage diagnoses and mail delivery of diagnosis results) while Fortran handles the building time history response analyses, which constitutes the core of the first- and second-stage diagnoses. This was done to take advantage of Ruby's high portability (support for various operating systems) and high compatibility with other programs (or applications) while relying on Fortran–with its high computational speed–for the seismic response analysis of buildings involving high-level, large-scale computing. Note that in this paper, we used the general-purpose analysis software STERA_3D [6] for time history response analysis of the 3D frame model used in the second-stage diagnosis.

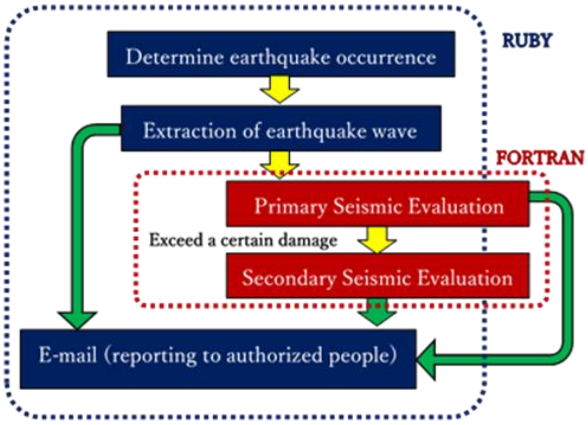


Figure 1. Flowchart and programming languages of the proposed real-time seismic diagnostic system operations.

III. BUILDING TRIAL OPERATIONS OF PROPOSED SYSTEM

For this study, we settled on Toyohashi City Hall in Aichi Prefecture for the trial operations. The municipal government offices consist of two buildings, the East Building and West Building, as shown in Fig. 2. The East Building is a 14-storey steel-framed reinforced concrete structure (SRC). The height is 46.1 m. The West Building is a 10-storey SRC structure. The height is 38.3 m.

Fig. 3 shows the profile of LAN seismometer and data recorder installations in the buildings at Toyohashi City Hall. LAN seismometers are installed on the 1st basement floor and 8th floor of the West Building and the 13th floor of the East Building; they constantly monitor vibrations on three components: East-West for the x direction, North-South for the y direction and vertical for the z direction. Vibration data are collected into one CSV file by the data recorder and uploaded intermittently to the cloud via an Internet router installed on the 4th floor of the West Building. Note that the Internet router is supplied with electrical power by an outlet connected to the city hall's private emergency power generator. In addition, the LAN seismometers and data recorder are provided with uninterruptible power supply (UPS) devices to ensure that the system operates for at least several hours after a disaster.

Figure 2. Full view of Toyohashi city hall.

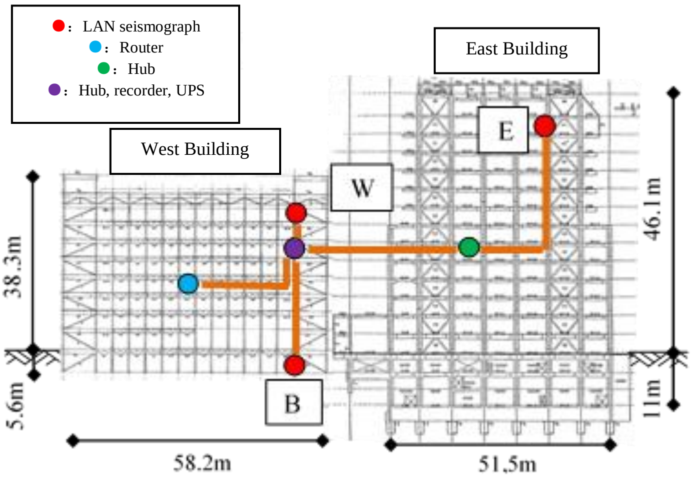
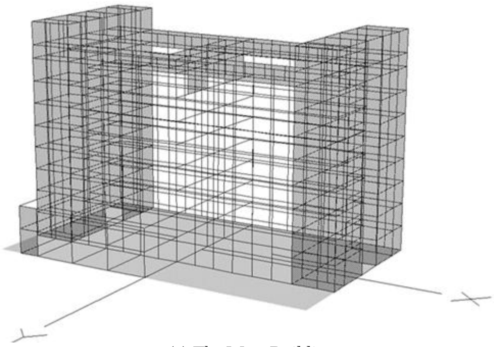


Figure 3. Profile of LAN seismometer and data recorder installations.

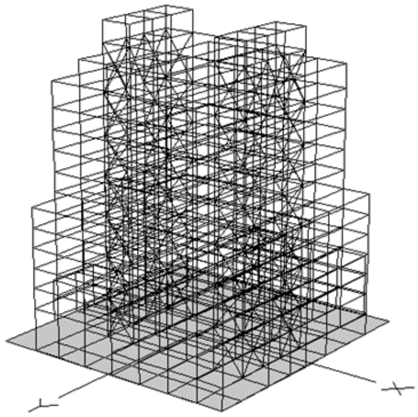
IV. TIME HISTORY RESPONSE ANALYSIS MODEL

Fig. 4 shows the analytical frame models for the second-stage seismic diagnosis, which were created using the earthquake response analysis software STERA_3D. The models assume rigid floors and beam-column joints with rigid panel zones. Walls and side columns are modeled as members with elasto-plastic shear springs, using multi-spring models for the axial and bending elements of columns and walls. The beam model has elasto-plastic flexural springs at both ends and an elasto-plastic shear spring at the center of the member. All the members have initial stiffness proportional damping and tri-linear hysteretic characteristics, with coefficients based on structural plans and drawings of both buildings provided by the city hall. A comparison between the natural periods of the 3D frame models and the results of microtremor observations on the actual buildings showed generally consistent results [7].

The MDOF lumped-mass model for use in the first-stage seismic diagnosis is assumed to have normal tri-linear hysteretic characteristics at each story, using constants determined by referring to the analytical frame model discussed above. More specifically, the 3D frame model is pushed over with an Ai load distribution up to a building drift angle of 1/50 and the capacity curve at each story is converted into a tri-linear model to simulate story response. Fig. 5 provides a comparison of the resulting tri-linear story models for use in the first-stage diagnosis and the capacity curves of the analytical frame model for use in the second-stage diagnosis using sample floors in both buildings.

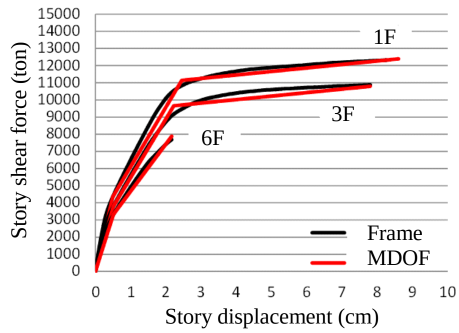


(a) The West Building

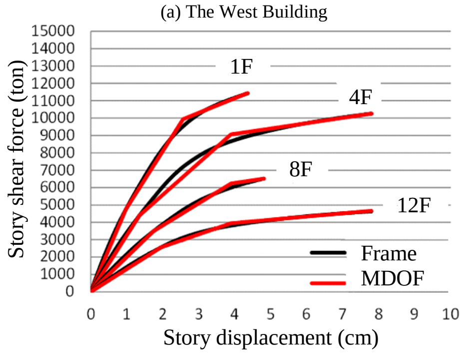


(b) The East Building

Figure 4. Analytical frame models of the Toyohashi city hall buildings.



(a) The West Building



(b) The East Building

Figure 5. Comparison of the MDOF models and frame models.

V. Results of Trial Operations for the 2018 Osaka Earthquake

6.1 magnitude earthquake struck at 7:58 am on June 18, 2018 in the northern part of Osaka Prefecture at a depth of about 13.2 km [2]. The earthquake produced strong tremors that peaked at the lower-6 level of the Japanese seismic intensity scale observed in Osaka Prefecture, which also reached Toyohashi City with shakings at about seismic intensity level 2 [8] (see Fig. 6). Figs. 7 to 9 show the earthquake ground motion waves observed from the three LAN seismometers installed in the buildings. With an earthquake threshold level of 1 gal (cm/s^2), the proposed system automatically made seismic observation record samples that were 123 seconds long, from 7:59:02 to 8:01:05, and sent an email notification with the earthquake information at 8:01:33.

The body of the email notification of the earthquake event that was automatically sent by the proposed system is reproduced below. Note that the CSV file of the sampled seismic records is attached to the email.

Body of email--
Date: June 18, 2018
Time: 07:56
Observed building: Toyohashi City Hall Bldgs.
Earthquake duration: 123.42 seconds

JMA seismic intensity level
Foundation: 2.16
8th floor, the West building: 2.93
13th floor, the East building: 3.72

Maximum acceleration observed
Foundation: 4.6 gal
8th floor, the West building: 15.51 gal
13th floor, the East building: 19.87 gal

Upon receiving the seismic record identification and sampling above, the real-time seismic diagnostic system automatically ran the process for the first-stage seismic diagnosis. For the trial operations of the Toyohashi City

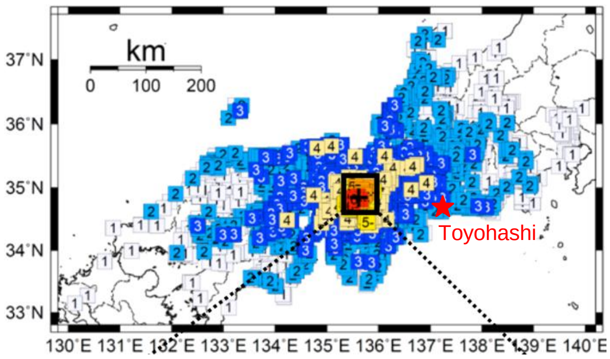


Figure 6. Seismic intensity distribution of 2018 Osaka earthquake [8]

Hall buildings shown in this paper, seismic response analysis of the MDOF model is performed by the automatic seismic diagnostic system server machine (OS: 64-bit Windows 10; CPU: Core i7-6700 3.40 GHz; Memory: 16 GB) installed at the Toyohashi University of Technology, the university affiliation of the authors. In the analysis, the seismic record at the 1st basement floor, West Building is used as the input ground motion of the buildings. Below are the contents of the email notification containing the first-stage seismic diagnostic results of the buildings under study, which was automatically sent by the proposed system.

Body of email--
Date: June 18, 2018
Time: 07:56
Observed building: Toyohashi City Hall Bldgs.
Earthquake duration: 123.42 seconds

North-South direction, the West Bldg.
Max. acceleration: 28.3 gal at 10th flr.

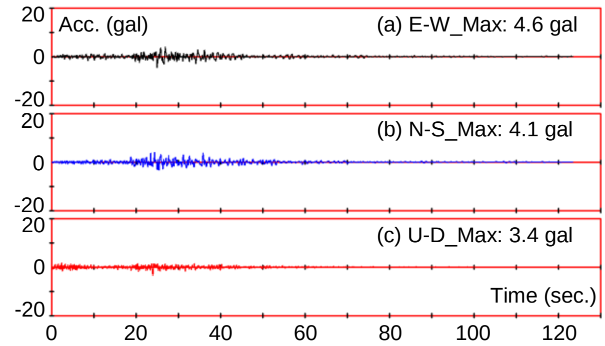


Figure 7. Seismic record at the 1st basement floor, the West bldg.

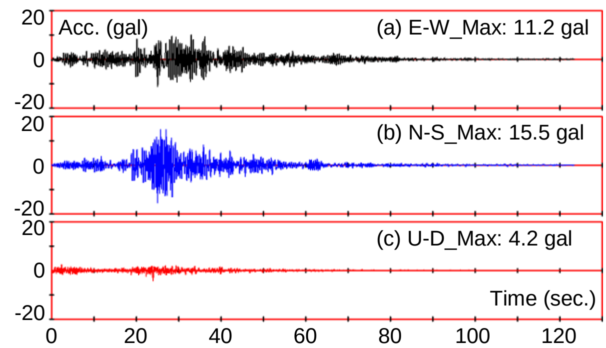


Figure 8. Seismic record at the 8th floor, the West bldg.

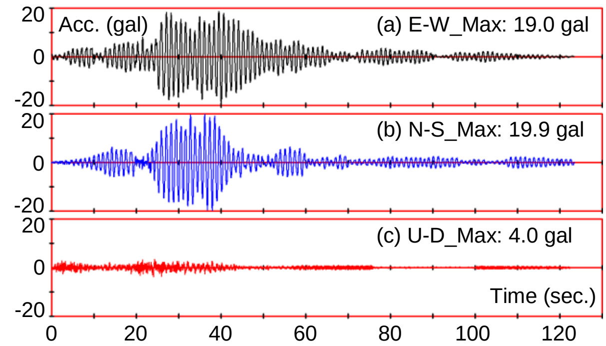


Figure 9. Seismic record at the 13th floor, the East bldg.

Max. velocity: 2.02 kine at 10th flr.
Max. displacement: 0.161 cm at 10th flr.
Max. story drift angle: 1/16694 at 3rd flr.

Max. ductility factor: 0.0114 at 3rd flr.
East-West direction, the West Bldg.
Max. acceleration: 31.2 gal at 10th flr.
Max. acceleration: 2.54 kine at 10th flr.
Max. displacement: 0.202 cm at 10th flr.
Max. story drift angle: 1/13003 at 4th flr.
Max. ductility factor: 0.0126 at 9th flr.
Results of simple seismic diagnosis
The West Bldg.: Safe

North-South direction, the East Bldg.
Max. acceleration: 16.5 gal at 14th flr.
Max. velocity: 3.21 kine at 14th flr.
Max. displacement: 0.653 cm at 14th flr.
Max. story drift angle: 1/6711 at 8th flr.
Max. ductility factor: 0.00928 at 7th flr.
East-West direction, the East Bldg.
Max. acceleration: 31.2 gal at 14th flr.
Max. acceleration: 5.52 kine at 14th flr.
Max. displacement: 1.07 cm at 14th flr.
Max. story drift angle: 1/4132 at 10th flr.
Max. ductility factor: 0.0167 at 11th flr.
Results of simple seismic diagnosis
The East Bldg.: Safe

The email notification of the first-stage seismic diagnostic results given above was went 1 minute, 32 seconds after the email notification of the earthquake event. And so, for this test case on the Osaka Earthquake, the earthquake event notification and first-stage seismic diagnostic results were sent to building administrators within two minutes after the earthquake ended.

Note that in the first-stage seismic diagnosis, the building status is assessed using three levels: safe, caution required and dangerous, with their respective thresholds specified below, according to the JSCA seismic performance table [9].

- Safe: Maximum interstory drift angle < 1/150 and maximum ductility factor < 0.5

- Caution required: Maximum interstory drift angle at 1/150-1/75 or maximum ductility factor at 0.5-1.0

- Unsafe: Maximum interstory drift angle > 1/75 or maximum ductility factor > 1.0

Therefore, both buildings were assessed as safe for this test case and the second-stage seismic diagnosis shown in the flowchart in Fig. 2 was not carried out.

As of October 2018, the proposed real-time seismic diagnostic system under trial operations at Toyohashi City Hall provisionally operates by sending such notifications to the authors as well as to Toyohashi City Hall crisis management supervisors, disaster prevention and crisis management officers, and the authorities at Toyohashi City fire department. In the future, we will continue to periodically coordinate with concerned parties in order to incorporate the system into the city's earthquake response and provide better facility operations during disasters.

VI. Conclusions

We conducted trial operations of our proposed real-time seismic diagnostic system in actual municipal government office buildings with a view toward its actual implementation. The system shares records taken by seismometers installed in the buildings to the cloud on the Internet in real time, and automatically notifies building administrators of the damaged condition and residual seismic performance of buildings after a disaster. After the Osaka Earthquake struck in June 18, 2018, the system was able to notify disaster prevention officials at the city hall of the results of the first-stage seismic diagnosis (simple diagnosis) within two minutes after the earthquake ended.

V. Future Work

Moving forward, we will continue to periodically consult and coordinate with concerned parties and pursue future studies along this line of research, such as preparing a procedures manual for building administrators to visually check building damage due to the disaster, and establishing a building facility operations framework during disasters for non-specialists with the assumption that the proposed system is used.

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