STRUCTURAL CONTROL AND HEALTH MONITORING
Struct. Control Health Monit. 2005; **12**:315–327

Risk monitoring of buildings with wireless sensor networks

Narito Kurata[1,*,†], Billie F. Spencer Jr.[2] and Manuel Ruiz-Sandoval[3]

[1] *Kobori Research Complex, Kajima Corporation, KI Building, 6-5-30, Akasaka, Minato-ku, Tokyo, 107-8502, Japan*
[2] *Nathan M. and Anne M. Newmark Endowed Chair in Civil Engineering and NCSA Senior Center Affiliate,*
University of Illinois at Urbana-Champaign, U.S.A.
[3] *Universidad Autonoma Metropolitana-Azcapotzalco, Mexico*

SUMMARY

Buildings are subjected to natural hazards, such as earthquakes and winds, and artificial hazards, such as fires and crimes, during their long-term use. Risk monitoring using a network of wireless sensors is one of the most promising emerging technologies for mitigation of these hazards. Recently, a smart sensor based on the Berkeley Mote platform was introduced, and an application to the next generation of structural health monitoring and control was proposed. The Mote has on-board microprocessor and ready-made wireless communication capabilities. In this paper, the performance of the MICA and MICA2 Mote is investigated through shaking table tests employing a two-storey steel structure. The acceleration sensor is tested, and its performance for wireless measurement and specific risk monitoring applications, such as damage detection in the structure, is presented. The MICA2 Mote is shown to have sufficient performance for the intended purpose. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: ubiquitous sensing; smart sensor; wireless sensor network; risk monitoring; damage detection; shaking table test

INTRODUCTION

Ubiquitous sensing/computing is expected to be realized over the next ten years. The interest in sensing technology for various uses has been growing, and new kinds of sensors have been developed by micro-electromechanical systems (MEMS) technology. Environmental information, such as brightness, temperature, sound, vibration, and a picture of a certain place in a building, is evaluated by the network to which a huge number of microcomputer chips with sensors were connected [1,2]. Figure 1 shows the flow towards a ubiquitous sensing/computing/networked society. A structural health monitoring technology will play an important role in this stream.

---

*Correspondence to: Narito Kurata, Kobori Research Complex, Kajima Corporation, KI Building, 6-5-30, Akasaka, Minato-ku, Tokyo, 107-8502, Japan.
† E-mail address: kuratan@kajima.com

Contract/grant sponsor: Curee-Kajima Joint Research Program

Received 24 August 2004
Revised 9 November 2004
Accepted 10 December 2004

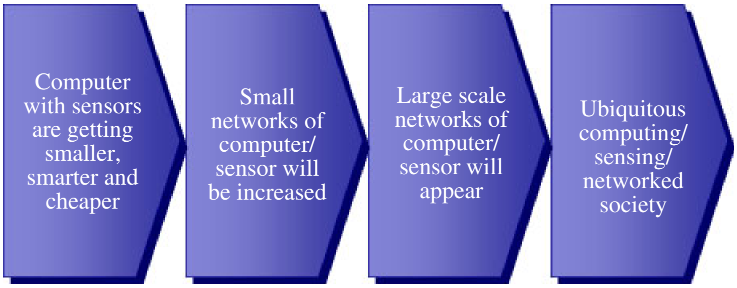

Figure 1. Towards a ubiquitous computing/sensing/networked society.

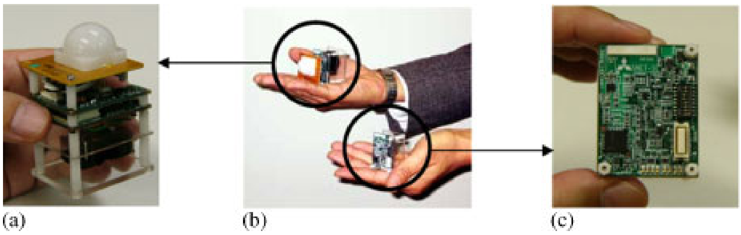

Figure 2. Wireless sensor network developed by Mitsubishi Electric Corporation [11]: (a) Prototype sensor node; (b) size comparison; and (c) wireless sensor board.

A number of studies have been conducted on structural health monitoring for buildings and civil engineering structures in recent years [3–6]. Some of these studies have focused on wireless sensing technology. Researchers at the Stanford University have developed a wireless sensing unit for real-time structural response measurements and conducted a series of validation tests [7,8]. Ruiz-Sandoval [9] developed an agent-based framework which is a hardware or software-based computer system that enjoys the properties of autonomy, social ability, reactivity, and pro-activeness for structural health monitoring. The Mitsubishi Electric Corporation has developed an energy-saving wireless sensor network as shown in Figure 2 [10,11]. Kawahara *et al.* [12] and the Oki Electric Industry [13] have devoted their effort to develop new wireless sensor networks as shown in Figure 3.

A commercially available wireless sensor platform called the Berkeley Mote with an operating system was provided by researchers at the University of California, Berkeley [14,15], and its application to the next generation of structural health monitoring and control was recently proposed [16,17]. Because of its open hardware and software platform, the Berkeley Mote is a useful tool for research activities. In this paper, the feasibility of monitoring of various risks for buildings using the smart sensors is discussed, and the performance of the MICA and MICA2 Mote as a wireless acceleration sensor is tested.

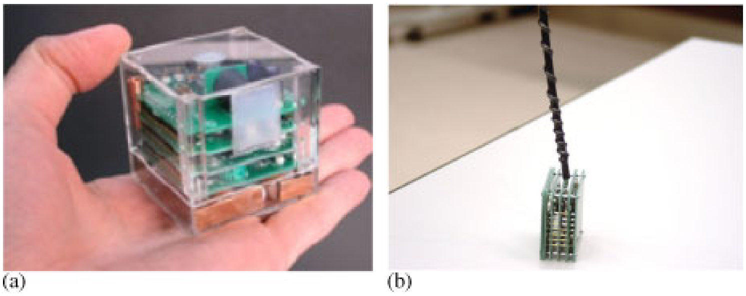

Figure 3. Wireless sensor networks: (a) U-cube developed at University of Tokyo [12]; and (b) as developed by Oki Electrical [13].

RISK MONITORING OF BUILDINGS

Buildings are subjected to natural hazards, such as severe earthquakes and strong winds, as well as artificial hazards such as fire, crime, and terrorism, during their long-term use. To mitigate these hazards, monitoring various risks in a building employing an intelligent sensor network is necessary. The sensor network could measure acceleration, displacement, strain, etc. The risk to buildings includes degraded structural performance, fatigue, damage, gas leaks, intrusions, fires, etc. According to the risk monitoring results, appropriate risk control measures (e.g. structural control, maintenance, evacuation guidance, warnings, alarms, fire fighting, rescue, security measures, etc.) can be applied (Figure 4).

A wireless sensor network plays an important role in such strategies and can be connected to the Internet so that this information can be used to monitoring future risks. Wireless sensors are easy to install, remove, and replace at any location, and are expected to become increasingly smaller [18] by using MEMS technology. They will provide a ubiquitous, networked sensing environment in buildings. For example, the acceleration and strain at numerous locations on each beam and column, temperature and light in each room, images and sounds in desired regions can be obtained by 'smart dust' sensors, as illustrated in Figure 5. Additionally, a single type of sensor such as a condenser microphone can be used for multiple purposes, for example, to detect earthquake, fires and intrusions [19]. Table I shows various kinds of hazards, and possible applications/combination of sensors.

WIRELESS SENSOR NETWORK MOTE

This technology is based on the smart dust project supported by the Defense Advanced Research Projects Agency (DARPA) [20] under the Network Embedded Software Technology (NEST) [21] program in the Wireless Embedded Systems at the University of California, Berkeley (Berkeley WEBS) [22]. The goal of this project is to explore the fundamental limits to the size of autonomous sensor platforms. Many new applications are expected to become possible when actual 'smart dust' can be realized on a millimeter size scale [18].

The MICA and MICA2 Mote (Figures 6 and 7) have been developed by researchers at the University of California, Berkeley. It is an open hardware and open software platform for smart

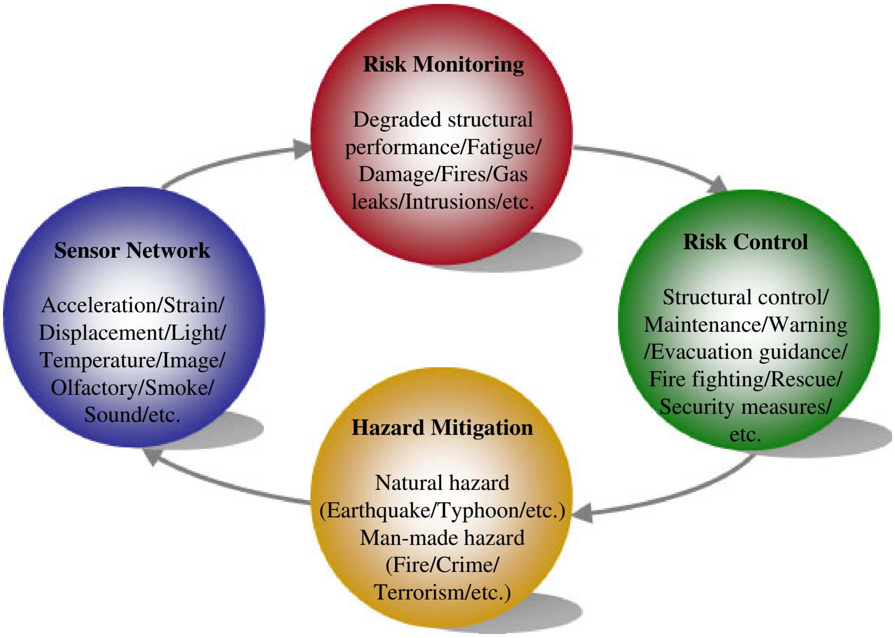

Figure 4. Building risk monitoring and hazard mitigation.

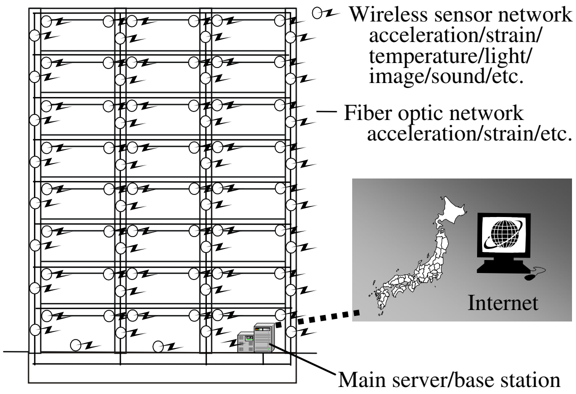

Figure 5. Example of risk monitoring system.

sensing and consists of plug-in sensor boards, processor, transceiver, and attached AA battery pack as shown in Table II. Many communication protocols could be used to ensure a reliability of the wireless communication.

TinyOS is a distributed, open-source operating system which supports large scale, self-configuring sensor networks as shown in Figure 8. TinyOS includes radio messaging, message hopping from Mote to Mote, low power modes, sensor measurements and signal processing; nesC is used as the programming language for TinyOS.

Table I. Sensor applications.

Hazard	Application	Sensor
Earthquake wind	Observation	Acceleration
	Experiment	Acceleration, strain
	Structural control	Acceleration
	Health monitoring, damage detection	Acceleration, strain, displacement
Fire	Fire detection	Temperature, smoke, acoustic, acceleration, olfactory
	Gas leak detection	Olfactory
	Alarm, warning	Sound
	Evacuation control	Temperature, smoke, acoustic, light, olfactory
Crime	Surveillance	Acceleration, acoustic, light, camera
	Security alert	Sound

Figure 6. MICA.

Figure 7. MICA2.

Table II. Specifications.

Processor/radio	MICA	MICA2	Remarks
CPU	ATmega103L	ATmega128L	
CPU clock	4 MHz	7.4 MHz	
Program memory	128 KB	128 KB	
Data memory	512 KB	512 KB .	
AD converter	10 bit	10 bit	
Processor current draw	5.5 mA	8 mA	Active mode
	< 1 μA	< 15 μA	Sleep mode
Radio frequency	916 MHz	315/433/868/916 MHz	
Data rate	50 KB/sec	38.4 K baud	
Radio current draw	12 mA	25 mA	Transmit
	1.8 mA	8 mA	Receive
	< 5 μA	< 1 μA	Sleep
Radio range	200 feet	1000 feet	
Power	2 AA batteries	2 AA batteries	
External power	3 V	2.7–3.3 V	

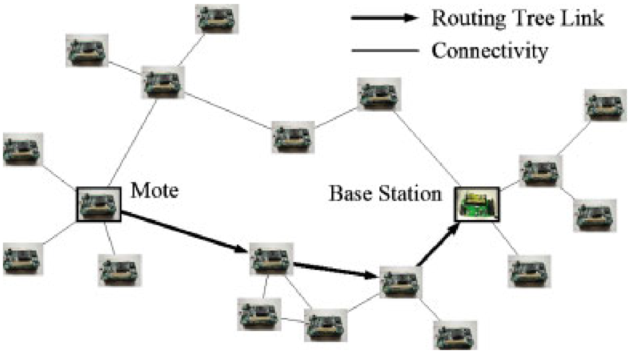

Figure 8. *Ad hoc* and multi-hop sensing.

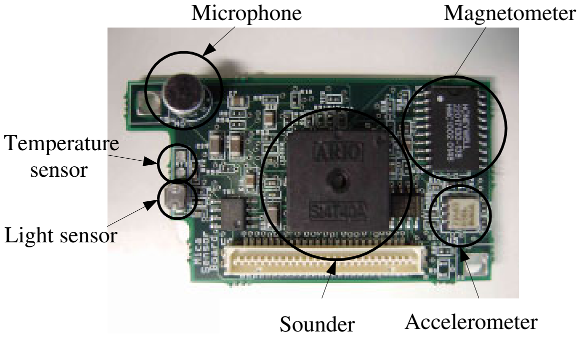

Figure 9. MTS310 sensor board.

A variety of sensor boards for the MICA and MICA2 are available. A MTS310 sensor board manufactured by Crossbow Technology, Inc. [23] which was used in this research, has acceleration, magnetic, light, temperature, and acoustic sensors, as well as a sounder (Figure 9). Other sensor boards can be designed and manufactured freely for specific purposes. For example, the Tadeo sensor board which is equipped with a high-sensitivity acceleration sensor has been developed and tested for civil engineering applications [24].

PERFORMANCE TEST

Free vibration test by MICA

To investigate the performance of the MICA as a wireless acceleration sensor, free vibration tests were conducted [25]. An 'oscilloscope' software application included in the TinyOS version 0.6 was used. Figure 10 shows the two-storey test structure which are made with duralumin for columns, and steel for beams. An additional mass of 3.3 kg is attached on each floor. The MICA and a reference accelerometer were attached to the test structure in each floor as shown in Figure 11.

Free vibration tests of structure A were conducted. Figure 12 shows measured accelerations at the top of test structure A using both the reference accelerometer and the MICA. Accelerations

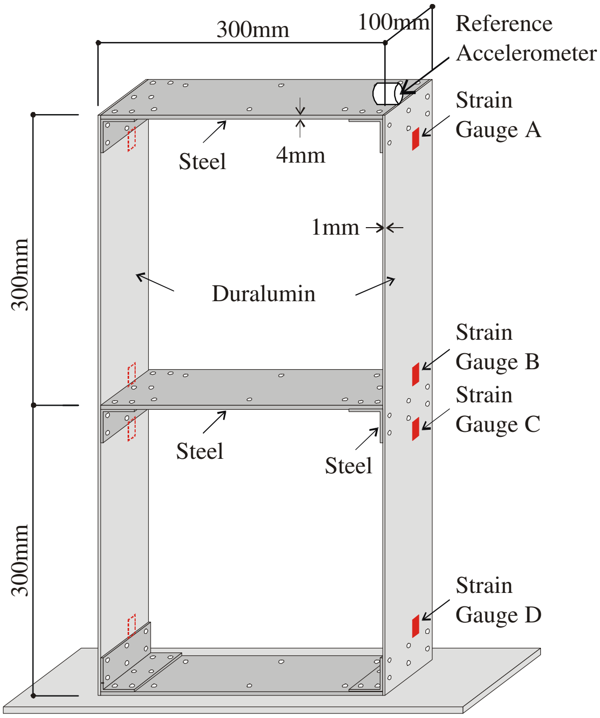

Figure 10. Test structure A.

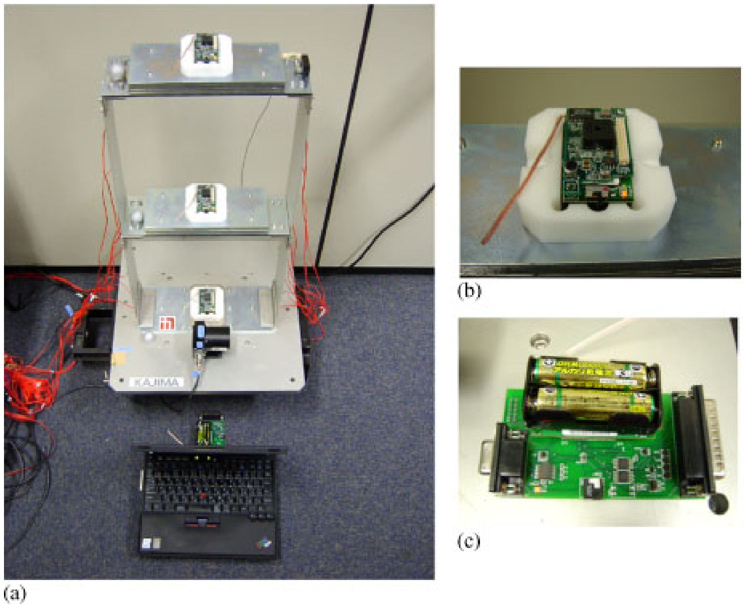

Figure 11. Test set-up: (a) Test structure A; (b) MICA; and; (c) Base station.

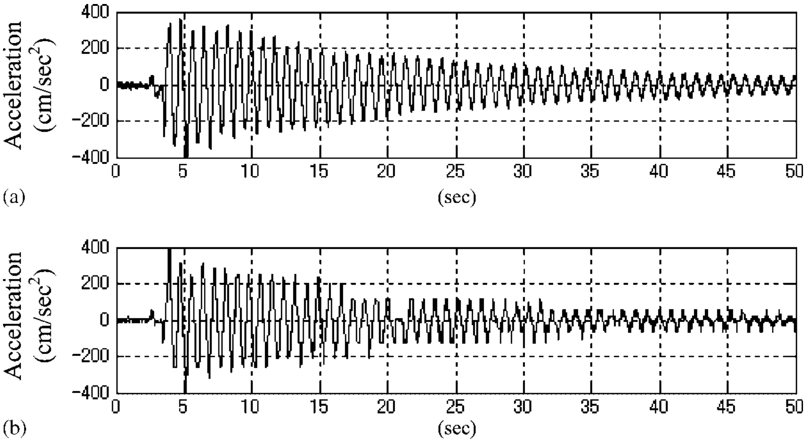

Figure 12. Free vibration test results: (a) Top acceleration by Reference; and (b) top acceleration by MICA.

measured with the sampling rate of 100 Hz by the MICA were sent wirelessly to the base station, which was attached directory to the notebook PC (see Figure 11). The sensitivity of the accelerometer on the MTS310 Sensor Board is not sufficient for accurate measurement of small amplitudes [24]. Additionally, some of data were lost during the test because of wireless communication problems which could not be identified. The maximum rate of data loss was

30%, although the distance between the MICA and notebook PC was within 1 m. The software for wireless communication with retry function would be required to meet the demand for the structural health monitoring.

Shaking table test by MICA2

It is necessary to deliver sensor data to the base station reliably. The application software, which was developed by the Open Systems Laboratory, the University of Illinois at Urbana-Champaign, was installed to the MICA2. The MICA2 has 512 KB of flash memory and it is possible to record over 200 s continuous data at 100 Hz. The MICA2 first store sensor data in the flash memory and then, send them to the base station later. It runs on the TinyOS version 1.0 and has a re-try function for sending the information to the base station from each MICA2. Shaking table tests were conducted to investigate the performance of the MICA2. Figure 13 shows the two-storey test structure considered with elastoplastic beams and columns. They are

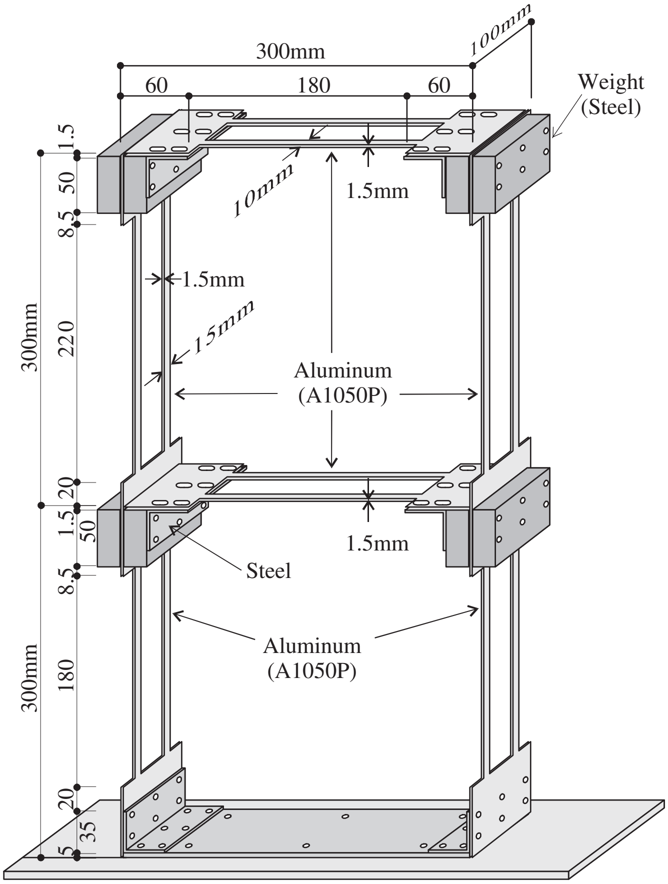

Figure 13. Test structure B.

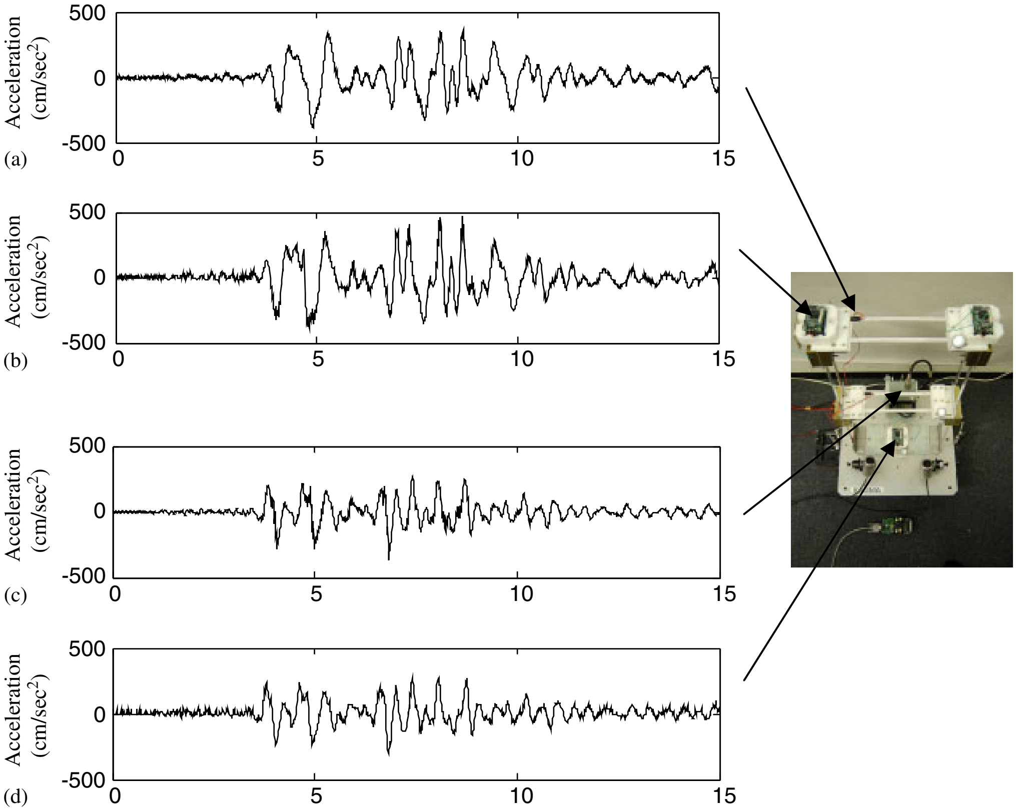

Figure 14. Shaking table test results: (a) Top acceleration by reference; (b) top acceleration by MICA2; (c) base acceleration by reference; and (d) base acceleration by MICA2.

made with aluminum for columns and beams. The MICA2 and a reference accelerometer were attached to the top and base of the test structure as shown in Figure 15.

The input excitation was the JMA-Kobe (NS) earthquake. Figure 14 shows measured accelerations for test structure B using both the reference accelerometer and the MICA2 for the case of an input peak acceleration of 371 cm/s^2. Accelerations from the three units of the MICA2 were sent wirelessly to the base station attached directly to the notebook PC wirelessly (Figure 15). The communication reliability was greatly improved so that only 0.5% of data were lost during the test because of the re-try function used for the wireless communication. Accelerations measured by the MICA2 at the top and base of the test structure agree with results by reference accelerometer. The accuracy of the measurements using MICA2 was also recognized.

Damage detection tests for structure B were carried out using the shaking table. The peak value of the input acceleration was 428 cm/s^2. Figures 16 and 17 show the damage process for test structure B, and the measured top-floor acceleration and strain in the columns, respectively. The first storey collapsed at stage 2 and 3 of the process, subsequently

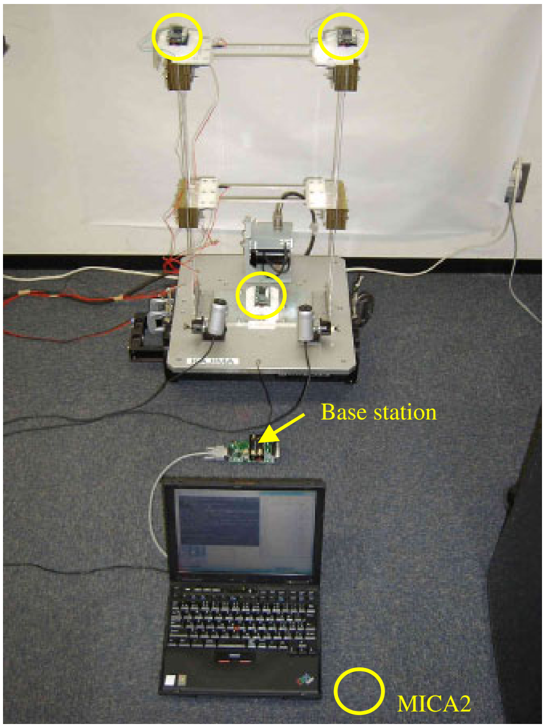

Figure 15. Test set-up.

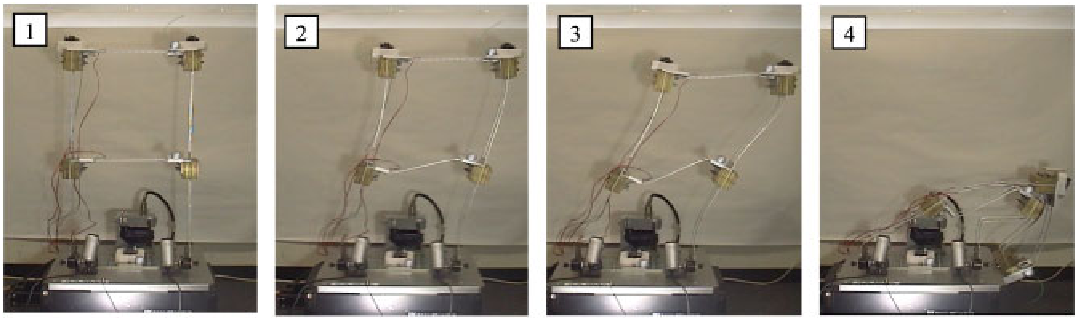

Figure 16. Damage process.

the second storey collapsed at stage 4, as shown in Figure 16. Comparing measured results between reference accelerometer and the MICA2, the MICA2 was able to measure the response of the structure wirelessly with minimal data loss. It is expected that the MICA2 could detect the damage of the structure by using the processor.

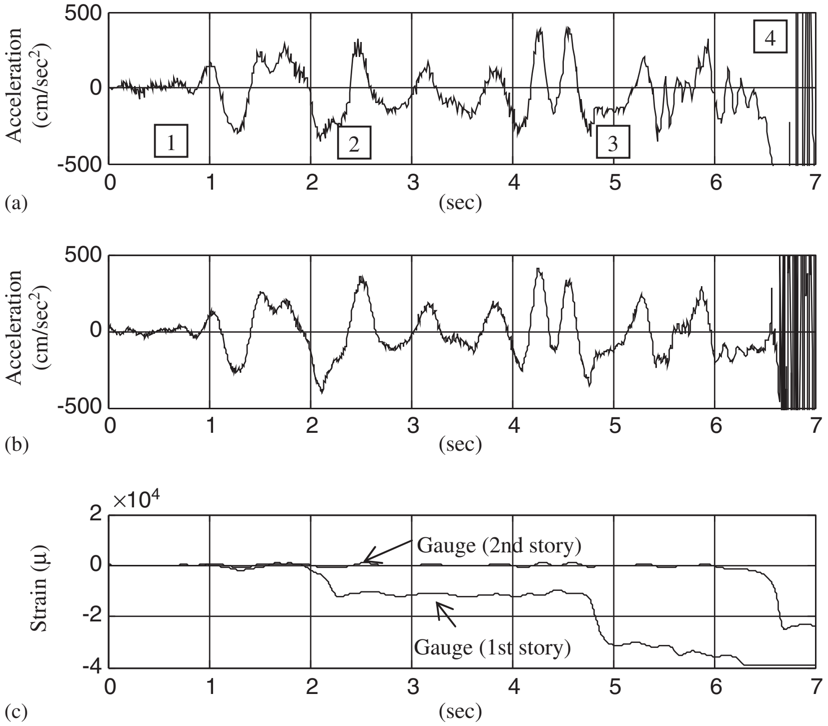

Figure 17. Damage detection test results: (a) Top acceleration by MICA2; (b) top acceleration by reference; and (c) strain of column.

CONCLUSIONS

The feasibility of risk monitoring for buildings using the smart sensors has been discussed, together with the performance of the MICA and MICA2 Mote as a wireless sensor. The MICA2 was able to measure the top acceleration of the test structure wirelessly during the large earthquake with minimal data loss. The effectiveness of the measurement was recognized by a comparison of measured results between reference accelerometer and the MICA2. The results showed the MICA2 has a promising future as an effective tool for risk monitoring in buildings.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to Professor Gul Agha and Mr Kirill Mechitov of the Open Systems Laboratory at the University of Illinois at Urbana-Champaign for development of the communication software for the MICA2. The authors would like to express their gratitude to Dr Yuji Miyamoto, Dr Yuji Sako, Mr Tetsushi Watanabe, and Mr Michio Imai of Kajima Corporation for implementing the shaking table tests. The authors gratefully acknowledge the partial support of this research by the CUREE-Kajima Joint Research Program Phase-V.

REFERENCES

1. Sakamura K. *Ubiquitous Computer Revolution*. Kadokawa Shoten: Tokyo, 2002 (in Japanese).
2. Weiser M. The computer for the 21st century. *Scientific American* 1991; **265**(3):94–104.
3. Spencer BF, Ruiz-Sandoval M, Gao Y. Frontiers in structural health monitoring. *Proceedings of the China-Japan Workshop on Vibration Control and Health Monitoring of Structures and Third Chinese Symposium on Structural Vibration Control*, Shanghai, 2002.
4. Dyke SJ, Caicedo JM, Johnson EA. Monitoring of a benchmark structure for damage identification. *Proceedings of the Engineering Mechanics Speciality Conference*, 2000.
5. Fujino Y, Abe M. Structural health monitoring in civil infrastructures and research on SHM of bridges at the University of Tokyo. *Proceedings of the Third World Conference on Structural Control*, vol. 1, 2002; 125–140.
6. Iwan WD. R-SHAPE: a real-time structural health and performance evaluation system. *Proceedings of the US-Europe Workshop on Sensors and Smart Structures Technology*, 2002; 33–38.
7. Lynch JP, Kiremidjian AS, Law KH, Kenny T, Carryer E. Issues in wireless structural damage monitoring technologies. *Proceedings of the Third World Conference on Structural Control*, vol. 2, 2002; 667–672.
8. Lynch JP. *Decentralization of wireless monitoring and control technologies for smart civil structures*. Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University, 2002.
9. Ruiz-Sandoval M. *Smart sensors for civil infrastructure systems*. Ph.D. Dissertation, University of Notre Dame, 2004.

10 Sato M, Tokunaga Y, Akeboshi Y, Shiga M. Low-power application-specific systems for sensor network node. *Proceedings of the 2003 IEICE General Conference*, Sendai, c-12-16:85, 19–22 March, 2003 (in Japanese).

11. Mitsubishi Electric Corporation. News release, http://www.mitsubishielectric.co.jp/news/2004/0126-a.htm, 2004 (in Japanese).
12. Kawahara Y, Minami M, Morikawa H, Aoyama T. Design and implementation of a sensor network node for ubiquitous computing environment. *Proceedings of IEEE Semiannual Vehicular Technology Conference* (*VTC2003-Fall*), Orland, USA, October 2003.
13. Skyley networks. *Seminar on Sensor Network*, Tokyo, April 21, 2003 (in Japanese).
14. Horton MA, Glaser S, Sitar N. Wireless networks for structural health monitoring and hazard mitigation. *Proceedings of the US-Europe Workshop on Sensors and Smart Structures Technology*, 2002; 19–23.
15. Wait JR, Tanner NA, Sohn H, Farrar CR. Application of a wireless sensor module as a distributed structural health monitoring solution. *Proceedings of the Third World Conference on Structural Control*, vol. 2, 2002; 35–41.
16. Spencer BF. Opportunities and challenges for smart sensing technology. *Proceedings of the First International Conference on Structural Health Monitoring and Intelligent Infrastructure*, Tokyo, vol 1: 65–71, 2003.
17. Spencer BF, Ruiz-Sandoval M, Kurata N. Smart sensing technology. Opportunities and challenges. *Journal of Structural Control and Health Monitoring* 2004; **11**:349–368.
18. Pister KSJ, Kahn JM, Boser BE. Smart dust: wireless networks of millimeter-scale sensor nodes. *Highlight Article in 1999 Electronics Research Laboratory Research Summary*, 1999.
19. Yamasaki T, Watanabe K. Security system by condenser microphone. *Proceedings of the 18th Sensing Forum*, 2001; 261–265 (in Japanese).
20. DARPA. http://www.darpa.mil/.
21. NEST. http://webs.cs.berkeley.edu/nest-index.html.
22. Berkeley WEBS. http://webs.cs.berkeley.edu/.
23. Crossbow Technology Inc. http://www.xbow.com/.
24. Ruiz-Sandoval M, Spencer BF, Kurata N. Development of a high sensitivity accelerometer for the mica platform. *Proceedings of the 4th International Workshop on Structural Health Monitoring*, Stanford, 1027–1034, 2003.
25. Kurata N, Spencer BF, Ruiz-Sandoval M, Miyamoto Y, Sako Y. A study on building risk monitoring using wireless sensor network MICA-Mote. *Proceedings of the First International Conference on Structural Health Monitoring and Intelligent Infrastructure*, Tokyo, vol 1: 353–357, 2003.
26. Tiny OS. http://webs.cs.berkeley.edu/tos/.
27. Sundresh S, Agha G, Mechitov K, Kim W, Kwon Y. Coordination services for wireless sensor networks. *Proceedings of the International Workshop on Advanced Sensors, Structural Health Monitoring, and Smart Structures*, Tokyo, 10–11 November, 12–17, 2003.
28. Kling RM. Intel Mote: an enhanced sensor network node. *Proceedings of the International Workshop on Advanced Sensors, Structural Health Monitoring, and Smart Structures*, Tokyo, 10–11 November, 92–96, 2003.