RAPID DAMAGE ASSESSMENT PROCEDURE TO COLLECT, PROCESS, AND ANALYZE DATA FOR MONITORING OF FULL-SCALE TESTS

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Abstract

This paper presents the application of modern survey techniques in collecting damage data of full-scale shake table tests in order to preserve their time-sensitive outcomes for future researchers. This study utilized modern instruments, especially Light Detection and Ranging (LiDAR) scanners, to collect damage data from shake table experiments of two full-scale wood residential buildings tested at the E-Defense facilities in Miki, Japan. The two buildings had identical plan views but had major differences in their structural design and base support conditions. Building A had diagonal wood bracing as its main lateral force resisting system, while Building B had shear walls with plywood sheathings as its lateral force resisting system. The experimental schedule included four days of testing with varying shaking intensities and base support conditions. Building A was initially located on a base isolation system, and subsequently fixed to the foundation for the third and fourth day of testing. Building B was initially located on a near-field soil to simulate soil-structure interaction, while it was fixed on the last day of testing. This study utilized close- and long-range LiDAR scanners to collect comprehensive 3D point clouds of the interior and exterior of the buildings after each test day, as well as a number of times in-between tests. Based on lessons learned, a survey protocol is proposed to be followed by researchers planning to conduct data collection from shake table tests using modern instrumentation in the future. The protocol includes the necessary actions prior, during, and after the experiments. In addition, advantages of the LiDAR scans over ordinary visual inspections and their capabilities are discussed by demonstrating a number of examples of the application of the collected LiDAR scans to detect and quantify damage in structural and nonstructural components of the two buildings. The results show the efficacy of collecting time-sensitive data using modern techniques as well as the accuracy of the collected data to conduct such measurements.

Keywords: LiDAR scanning; Shake table tests; Full-scale tests; Damage detection; Wood buildings

1 Introduction

This paper targets the use of modern survey techniques, and especially Light Detection and Ranging (LiDAR) scanning, to collect time-sensitive data from full-scale shake table experiments. A five-year project named “Tokyo Metropolitan Resilience Project” is currently in progress in Japan to study the resilience of urban infrastructure and communities. As the first stage of this project, a number of shake table tests were conducted on two wood residential buildings on the largest shake table in the world at the E-Defense facility in Miki, Japan. This paper presents and summarizes the outcomes and advantages of utilizing modern survey techniques to collect damage observations and data from these tests, along with a proposed survey protocol for future survey studies. Observations made through visual inspections and modern techniques are also compared and discussed.

A wide range of natural hazards occur each year in the United States (U.S.) and around the world that threaten the resilience of communities. Increasing occurrence rates cause communities to suffer direct and indirect impacts, as well as long periods of recovery. Many studies in the literature have studied the hazard loads, their impacts, the restoration of communities after disasters, as well as strategies to improve the resilience of communities subject to these events [1–10]. Having relevant data is one key element of such studies, which can be collected from various types of resources, including reconnaissance field study data and experimental studies. These data usually are considered as time-sensitive data since they are available for a limited amount of time and they vanish very fast. For example, experimental data vanishes after demolition of the specimens, while disaster damage data vanishes when communities start to recover. Collecting time-sensitive data of full-scale shake table tests, which is the focus of this paper, is of great value and importance since such experiments are very costly and need special facilities to conduct them.

Various forms of survey exist in the literature to collect time-sensitive data after disasters or during experimental studies. To collect damage and recovery data after natural disasters, a wide range of methods can be found in the literature, including field inspections [1,11,12], Unmanned Aerial Vehicle (UAV) images [13], geospatial videos [14,15], as well as LiDAR scanning [16]. Additionally, in lab-controlled experimental studies, various methods are employed to collect data, including a combination of visual inspections and traditional instrumentation (e.g., accelerometers) [17,18], LiDAR scanning [19], and digital image correlation [20]. The number of studies employing modern survey instruments over traditional reconnaissance field studies is increasing rapidly during recent years. There are various advantages of using modern survey techniques in order to collect data after disasters. For example, after major disasters, access to damaged areas is difficult and in some cases impossible. It is usually not safe to do field surveys, and hence, modern survey techniques such as remote sensing methods are preferred with a much faster process. However, there are shortcomings in such data collection methods such as low level of details in damage detection compared to the field inspections; studies in the literature, such as Zhou et al. [19], are trying to address these shortcomings.

The focus of this paper is to utilize modern survey techniques, and specifically LiDAR scanning, in full-scale shake table experiments. Various studies in the literature used LiDAR scanning to collect a 3D point cloud of damaged infrastructure after major disasters. Yu et al. [21] collected damage data of a severely damaged 18-story building in Nepal after the 2015 Gorkha earthquake (with moment magnitude of 7.8) using LiDAR scanning, while quantifying the damage of two key components of this building (beam coupling and infill walls) using the resulting point clouds. Zhou et al. [16] developed a methodology using LiDAR airborne data to first locate buildings, and then identify and quantify the damage in each of them. Among the few lab-controlled studies which employed LiDAR scanning, Kashani and Graettinger [19] developed a clustering-based algorithm to automatically identify roof damage using the developed LiDAR point clouds. The current study will demonstrate the capabilities of LiDAR scanning in collecting damage data, and detecting and quantifying damage.

Two full-scale wood buildings, representing typical residential buildings in urban areas in Japan, were tested over four test days on the E-Defense shake table facility, in Miki, Japan. Fig. 1 presents photos taken during the experiments from the four corners of the shake table. One of the buildings, named “Building A,” as shown in Fig. 1, had diagonal wood bracing as its main lateral force resisting structural system, while the other building, named “Building B” had shear walls with plywood sheathing as its main lateral force resisting system. Building A was placed on a base isolation system during the first two days, but it was subsequently fixed on the shake table for the remainder of the experiments. Building B was placed on a soil box for the first two days of testing, while during the third day simple base isolation system with steel rails to facilitate movement was placed underneath to control its movement, and it was fixed on the shake table for the last test day. Both buildings were constructed with full nonstructural details, pipelines inside the building (and inside the soil box for Building B), and all furniture of a regular urban Japanese house. Table 1 summarizes the foundation details and shaking intensities on each test day for both buildings.

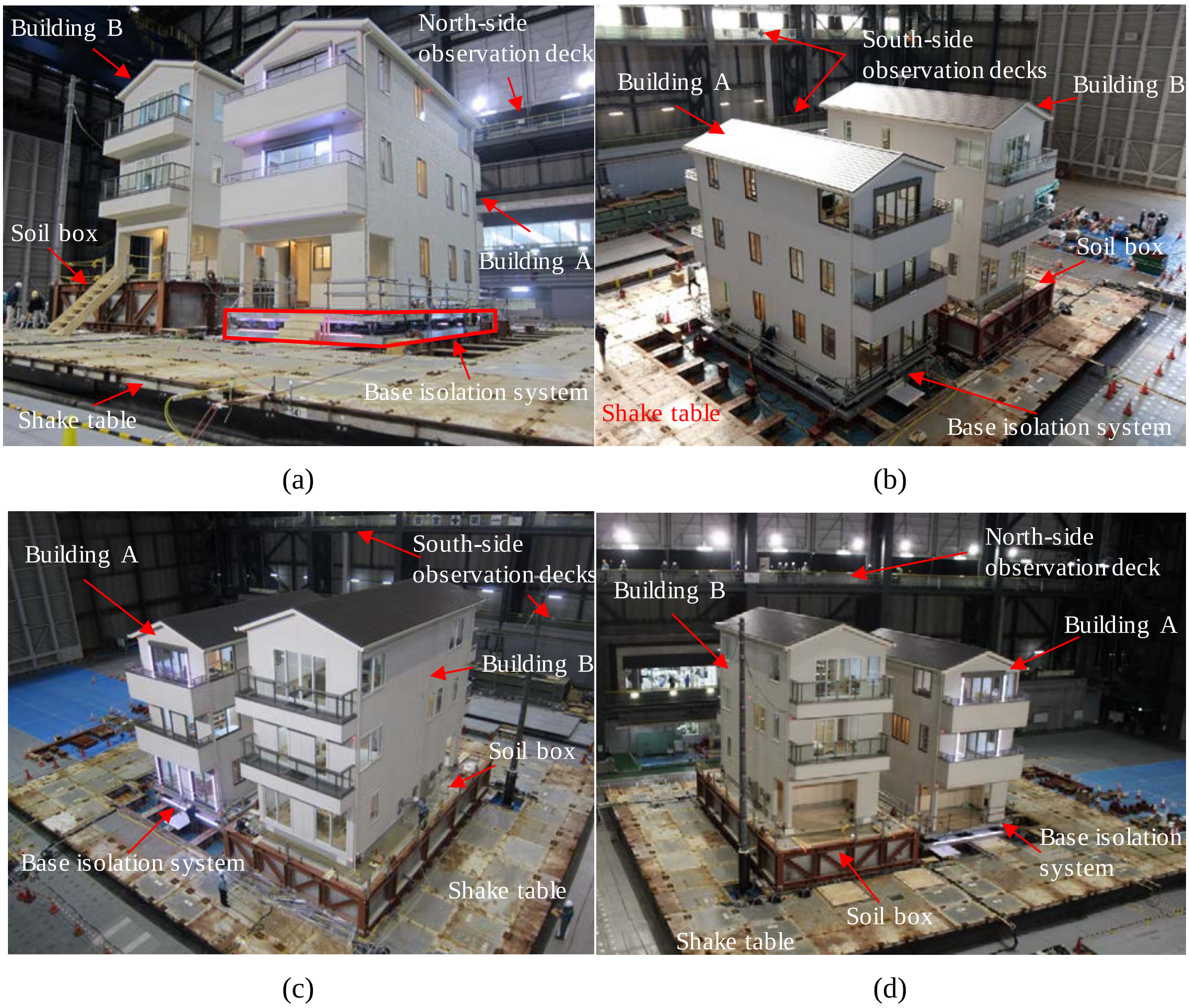


Fig. 1: Photos of the four corners of the Buildings A and B on the shake table from: (a) Southeast, (b) Northeast, (c) Northwest, and (d) Southwest.

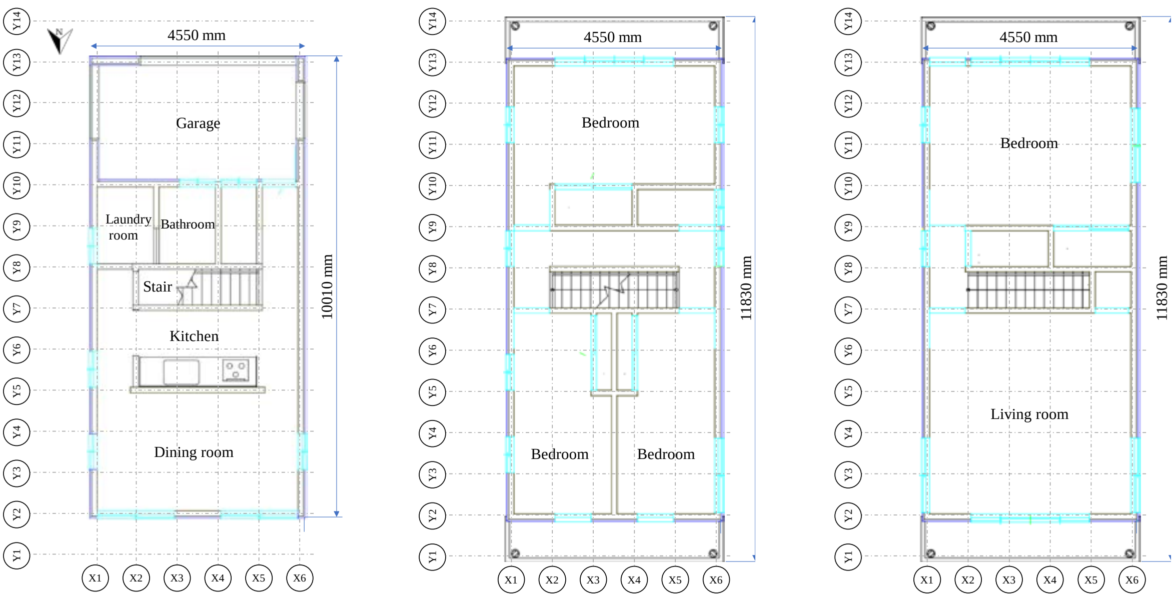
Table 1: Details of foundation condition and shaking intensities on each test day.

Building ID	**Test day 1**		**Test day 2**		**Test day 3**		**Test day 4**	
	Testing Configuration Variables							
	Base condition	*Shaking intensities*	*Base condition*	*Shaking intensities*	*Base condition*	*Shaking intensities*	*Base condition*	*Shaking intensities*
Building A	Base-isolation	JMA* 25% JMA 50% JR** 25% JR 50%	Base-isolation	JMA 100% JR 100%	Fixed	JMA 25% JMA 50% JMA 100% JR 100%	Fixed	JMA 100%
Building B	Soil-box		Soil-box		Soil-box with steel rails		Fixed	

*Kobe JMA record
**Takatori JR record

2 Test specimens

The two buildings in this study are very similar in appearance and dimensions, but their structural configurations are very different. Fig. 2 presents the plan view of Building A. The total area of the building is 161.5 m^2, while the first and second story are 2.775 meters high and the third floor is 2.769 meters high. This building as demonstrated in Fig. 2 is a typical townhouse in urban areas of Japan. A kitchen, dining room, bathroom, and laundry room were located on the first floor, while three bedrooms were located on the second floor and one master bedroom and a living room were on the third floor. Building A had a network of wood bracings as the main seismic lateral resistor, while Building B had wood shear walls on its perimeter for this purpose.



(a) (b) (c)

Fig. 2: Architectural layout (plan view) of the specimens; (a) story 1, (b) story 2, and (c) story 3.

3 Instrumentation

Various instruments were utilized in this study to record damage as well as the structural response of the buildings. Two types of LiDAR scanners were employed to scan the interiors and exteriors of the buildings after each test day, while some exterior scans were conducted in-between tests whenever possible. The LiDAR scanners were provided by the Natural Hazards Engineering Research Infrastructure (NHERI)

RAPID facility with the following details: (i) two close-range Leica BLK 360 LiDAR scanners, and (ii) one long-range Maptek I-Site LR3 LiDAR scanner. Leica BLK 360 has a scanning distance range of 60 meters with an accuracy of 4 mm in 10 meters distance and was mainly used to scan the building interiors, while the Maptek scanner has a scanning distance range of 1,200 meters with an accuracy of 4 mm and was mainly used to scan the exterior of the buildings. The majority of the exterior scans were conducted from the observation decks around the laboratory, shown in Fig. 1, and thus, the close-range scanner was not suitable for this purpose. In addition, the coordinates of multiple targets on the two buildings and also on the laboratory walls were collected using a total station (Leica Nova TS16I) in order to assemble the scans with added precision and efficiency. Furthermore, a thermal camera (Flir C3 Thermal Camera) was utilized to identify invisible water leakage of the pipelines buried inside the soil box.

4 Proposed survey protocol

A survey protocol using modern instruments, including LiDAR scanners, is proposed in this study to minimize the challenges experienced during the project. This protocol is demonstrated in Fig. 3, and includes the actions required to be taken before going to the laboratory, preparations inside the laboratory before the tests, technical preparations before each scanning day, actions during scanning, and actions after each scanning day. Note that, in this study, LiDAR scanning was conducted from the building interior and exterior in the morning of each test day, while exterior scanning was conducted whenever feasible in-between tests using the long-range LiDAR scanner from observation decks around the laboratory to minimize impact to shake table testing schedule. The resulting scans were registered and post-processed afterwards, which is outside the scope of this paper, but following actions in this figure make post-processing much easier.

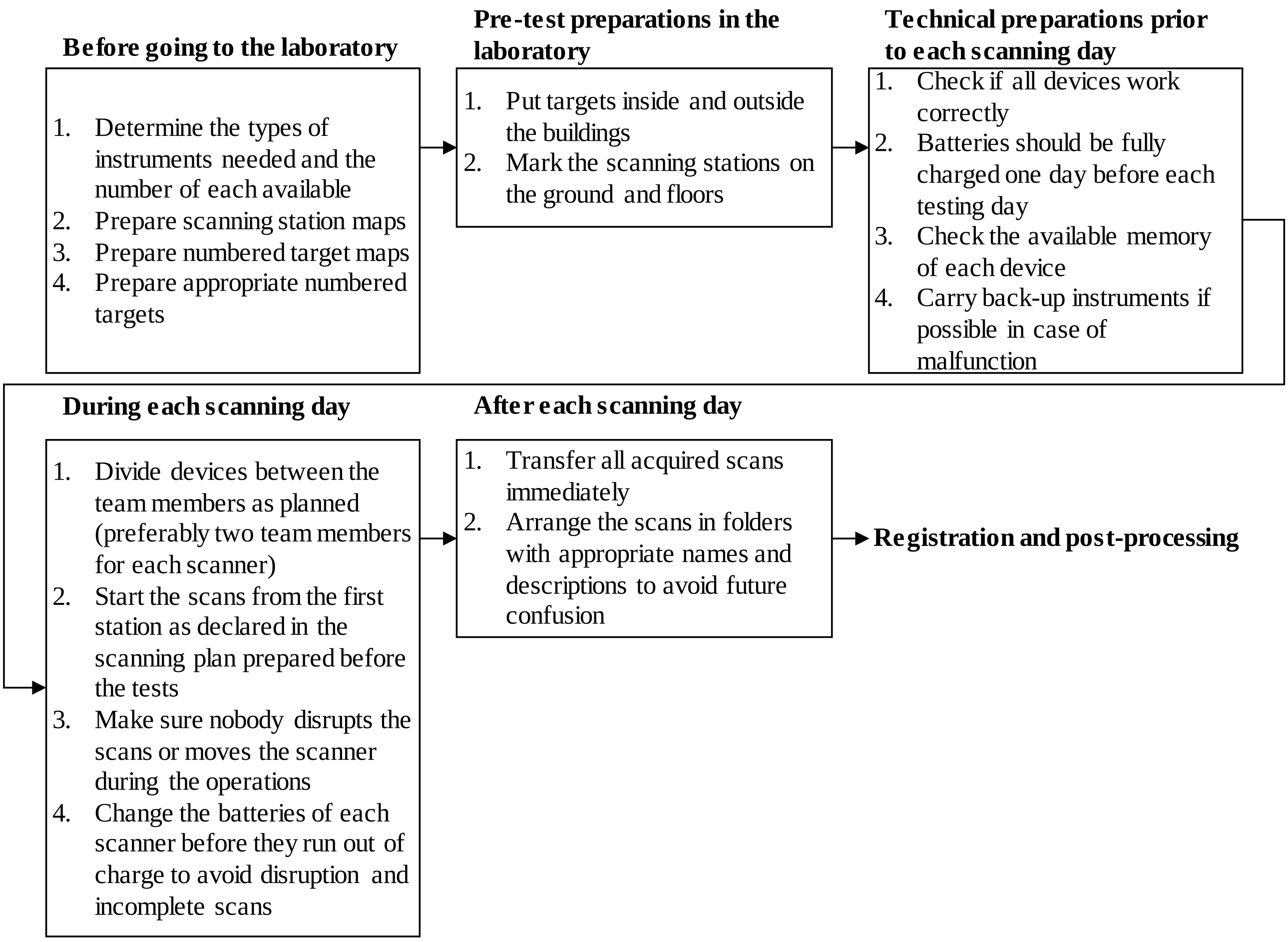


Fig. 3: Proposed protocol for LiDAR scanning of full-scale shake table tests.

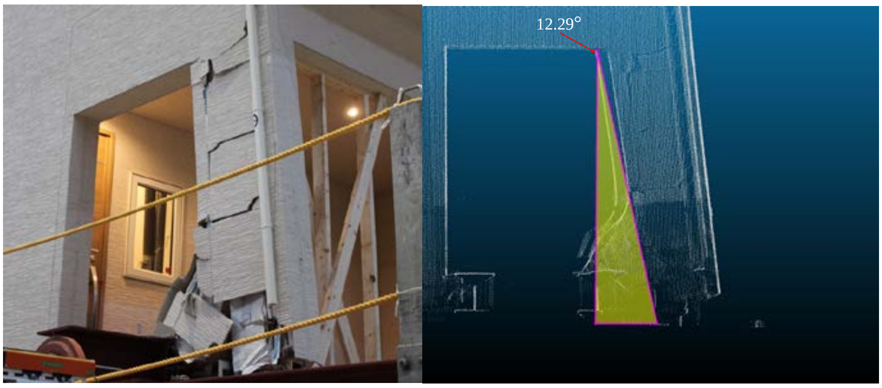
5 Damage Assessment

In this section, examples of the capabilities of the resulting LiDAR point clouds to detect and measure damage are provided for the structural and nonstructural components. Registration and post-processing resulted in a 3D view of the buildings for each scanning phase; an example is presented in Fig. 4.

Fig. 4: A screenshot of the 3D view of the two buildings point clouds.

No major structural damage was observed in the first two days of testing, and hence, neither the LiDAR scans nor the visual inspections revealed any structural damage. During the next two test days, structural damage occurred, while during Test Day 4 damaged structural components were exposed due to the severity of the damage. Fig. 5 presents two examples of the structural damage in Building A (Fig. 5a and 5b) and Building B (Fig. 5c and 5d) on Test Day 4. Fig. 5a shows a photo taken from a damaged diagonal wood bracing in Building A using a camera, while Fig. 5b shows a screenshot of the LiDAR point cloud of this element with a number of measurements. The comparisons illustrate the advantage of LiDAR point clouds over ordinary visual inspections to store perishable data and allow researchers to perform post-mortem measurements. In a similar manner, Fig. 5c and 5d, respectively, present the photo and LiDAR point cloud of a distorted column in Building B and the rotation angle measured through the point cloud.

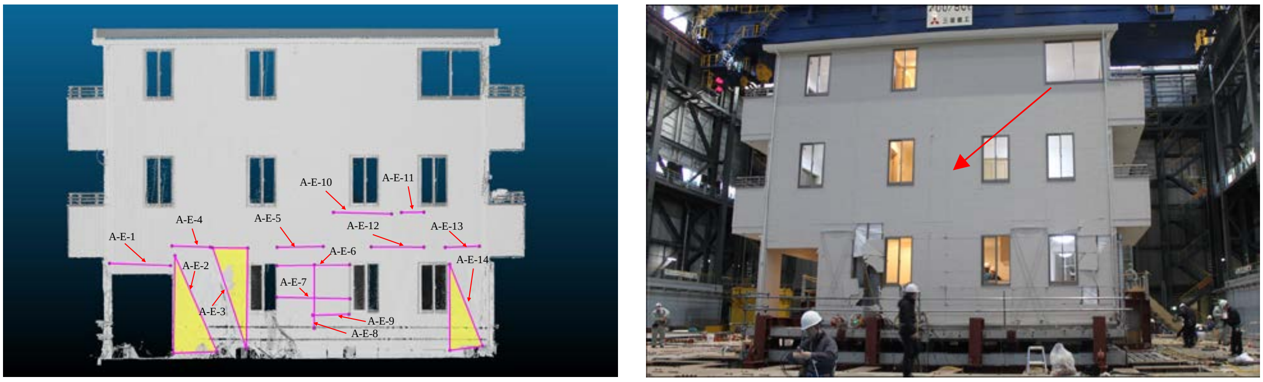
(a) (b)



(c) (d)

Fig. 5: Camera photos and LiDAR point cloud screenshots of ((a) and (b)) a damaged bracing in Building A and ((c) and (d)) a distorted column in Building B.

During the first two days of testing, when Building A was located on base isolation, very minor nonstructural damage was observed, while Building B experienced nonstructural damage from the first day of testing. Both buildings experienced severe structural damage in the last two days of testing. As an example of the nonstructural damage, Fig. 6 presents the façade damage on the eastern wall of Building A on Test Day 4. Fig. 6a shows a screenshot of the LiDAR point cloud of this damaged wall along with the detected damage marked by pink lines for cracks and yellow areas for the spalling, while Fig. 6b shows a photo of this wall taken using an ordinary camera during the visual inspection. The length of the cracks as well as the area of the spalled façade boards measured using the LiDAR point cloud are summarized in Table 2. As another advantage, LiDAR point clouds enable measurements on the buildings even after they are demolished.



(a) (b)

Fig. 6: Façade damage on the east-side wall of Building A; (a) a screenshot of the LiDAR point cloud and the detected damage, and (b) a photo taken using an ordinary camera during the visual inspection.

Table 2: Measurements of the marked damage on the eastern wall of Building A presented in Fig. 6.

Cracks		*Damaged areas*	
Label	Length (m)	Label	Area (m^2)
A-E-1	1.611	A-E-2	3.125
A-E-4	1.019	A-E-3	2.500
A-E-5	1.220	A-E-14	2.025
A-E-6	1.924		
A-E-7	1.945		
A-E-8	1.684		
A-E-9	0.968		
A-E-10	1.539		
A-E-11	0.594		
A-E-12	1.394		
A-E-13	0.904		

6 Conclusions

This study targets the use of modern survey techniques in collecting data from full-scale shake table experiments, especially the application of LiDAR scanning. Two full-scale wood residential buildings were tested on the largest shake table in the world at the E-Defense facilities in Miki, Japan, during four days of testing. Damage data collection process using LiDAR scanning was shown to be capable of preserving time-sensitive damage information for future studies. Based on many practical challenges experienced during this study, a survey protocol was proposed for other researchers planning to use modern survey techniques in future similar studies. This protocol encompasses actions required prior to arriving at the laboratory or site until after the LiDAR scanning is finished. In addition, this paper demonstrated the capability of the resulting point clouds to detect and measure both structural and nonstructural damage even after the tested buildings are demolished.

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